Indian Meterologist's Vade-Mecum

1875

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PART I.

PART II.

ADDITIONAL CORRIGENDA

IN THE

METEOROLOGY OF INDIA.

Page 108, line 31, *for* " directly as the absolute temperature," &c., *read* "directly as the square of the absolute temperature," &c.

" 192, line 33, *for* " I cannot think it likely," *read* " I cannot but think it likely."

" 221, *in heading of table, for* " seven," *read* " six," and the same on page 222.

CORRIGENDA AND ADDENDA

IN THE

INSTRUCTIONS TO OBSERVERS.

Page 59, in the list of symbols and weather initials, *insert*—

● . . . *r*. . . . Continued rain.

„ 79, line 12, *for* first and fifteenth, *read* first and sixteenth, *and for* February the fourteenth, *read* February the fifteenth.

„ 92, line 8, *for* 15th, *read* 16th.

CORRIGENDA AND ADDENDA

TO THE

METEOROLOGY OF INDIA.

Page 118, and other places throughout the work. *For* Dr. Henessey, *read* Mr. Henessey. I was not aware when writing, that the degree received by Mr. Henessey from the University of Cambridge was the rarer and very distinguished honour, the M. A. degree, conferred *honoris causâ.*

" 127, foot-note. The symbol ρ in Peslin's formula is the absolute density of dry air. That is to say, the weight in decimals of a pound (the mass unit) of one cubic foot (the unit volume) of dry air at the standard pressure and temperature.

" 144, foot-note. While the work was passing through the press, a telegraph line to False Point was sanctioned and constructed. Telegrams are now received daily from that important station.

" 155, foot-note, lines 2, 3; *after the word* "ascends," *insert* "in a given time, through a given height"; *and after the word* "descends," *insert* "in the same time, through the same height."

" 171. *In the formula—*

$$\frac{461 \cdot 2 + 6 \cdot 411}{461 \cdot 2 + 73 \cdot 81} \&c.$$

for 6·411, *read* 64·11.

" 242, foot-note, *for* "end of this work," *read* "end of this Chapter."

" 259, line 14, *for* "sub- $\frac{\sigma}{\rho}$ stitute for, &c.," *read* "substitute for $\frac{\sigma}{\rho}$ &c."

" 272, the mean temperature of Bareilly in February is 62·6 and not 66·6.

INDIAN METEOROLOGIST'S VADE-MECUM.

PART I:

INSTRUCTIONS TO OBSERVERS.

INTRODUCTION.

THE object of meteorological observation is to collect facts for studying the physical changes of the atmosphere, in order that we may gain therefrom a knowledge of their causes and their laws. This is a branch of physics, and requires therefore the same care, and the same precautions, that are demanded in all experiments and observations undertaken for the discovery of physical laws. It might be thought that so obvious an inference would scarcely need insisting on; and yet it is unquestionable that very many of those persons who keep a regular register of the readings of meteorological instruments, and who even devote much time and attention to the occupation, practically ignore it; and incur much disappointment when, perhaps after many years' assiduous labour, they are told by some one who has vainly sought to turn their registers to useful account, that, owing to the neglect of a few simple precautions, the whole of those results are of little or no value. A barometer and a thermometer are instruments of simple construction, and any person of ordinary intelligence may be taught in the course of a few minutes how to read them accurately. But it is of little use to be able to read them, unless we know exactly what is the physical meaning of the readings we record; in other words, unless we know how that particular condition of the instrument which is expressed by each reading has been brought about; and (since, in all cases, many causes have been at work to produce it, while we want to measure only one of them,) unless we can eliminate all that is foreign to our purpose, and so ascertain that one measure truthfully or within assignable limits of error. The best known of all meteorological instruments, the thermometer, will serve to illustrate these remarks. Take any four thermometers of different kinds and dimensions, and hang them, side by side, on a wall in a verandah or well-ventilated room. They will probably be found to differ from one-tenth of a degree to a degree in their readings, sometimes as much as two or three degrees. These differences may arise either from the fact that

the thermometers are not equally sensitive, or from errors in their graduation, such as affect almost all instruments more or less. If they arise from the first cause, they will disappear from the mean of a large number of readings, taken in about equal proportions with the temperature rising and falling. But if from the latter, however small they may be, they will affect to their full extent all registers of their readings, however extensive and varied, and all mean values computed therefrom; and to that extent they will falsify the required records; yet in India very few observers take the trouble to ascertain the errors of their instruments, and some who know them are too careless or too ignorant to correct them.

Having by due comparison determined the inherent errors of the instruments, so that, by applying corrections, their readings may be reduced to a common standard, suspend one of them in a well-ventilated room, another in a verandah, a third beneath a thatched shed open all round, and a fourth on an open stand, such as is recommended by Colonel James or Mr. Glaisher; all, of course, shaded from the sun. In these several positions let readings be taken in fine, dry weather, a few minutes before sunrise and again about three in the afternoon. In the first set of readings, the thermometer on the open stand will probably be one or two degrees lower than any of the others; next above it, will be that in the shed; next, that in the verandah; and highest of all will be that in the room. The afternoon readings will differ quite as much, but in the reverse order, the thermometer on the stand being highest, that in the room lowest; and the extreme difference may amount to as much as 5 or 6 degrees. Now, all these various kinds of exposure are practised, and yet it is seldom stated in the published returns which of them has been adopted. Such returns are, of course, not comparable with each other, and, if the facts are unknown, no one can make any use of them.

Lastly, it is not infrequent to find in the registers of temperature published in official reports, not the actual observations, but certain values which are called 'means.' But it is very rarely stated how these means have been computed. One person reads an ordinary thermometer at 10 A. M. and 4 P. M., and gives the average of the two readings; another gives the average of his maximum and minimum; and in some registers which lately came under my notice, this mean temperature was obtained by adding together the readings of a minimum and maximum thermometer recorded and re-set both at 10 A. M. and 4 P. M., and dividing by four. This really amounted to giving, as the mean temperature of the day, the average of the highest and lowest temperatures, of 10 in the morning and of 4 o'clock of the previous afternoon. The proper meaning of the term 'mean' will be explained further on; but it is clear that the results of the above three methods will all be different, and, indeed, only one of them even approximates to what the term is understood to imply.

In order, then, that a meteorological register may be of any value, the work of observation must be conducted intelligently, and with a number of precautions which can be appreciated only by trained physicists. Honesty—not always, alas! to be counted on—is, of course, a *sine quâ non.* But neither honesty nor zeal will suffice without knowledge. Such knowledge it is the object of this little treatise to convey, as far as is consistent with brevity, by means of short explanations and rules founded thereon. A little book on a somewhat similar plan, printed in 1868, for the guidance of observers in Bengal and elsewhere, has been found of much use in facilitating the meteorological work. This is now out of print, and, instead of simply re-printing it, I have considered it better to re-write the instructions, omitting some items that are unnecessary or obsolete, and embodying such additional matter as has been suggested by the increased experience gained during the last seven years. The first part of the book being intended simply as a guide to those who keep a meteorological register, I have not entered on the subject of meteorology as a science, further than is necessary for the due understanding of the methods of recording observations. In the second part I have entered upon some of the more important laws of pneumatics and thermotics that regulate meteorological phenomena; and I have given such a sketch of what is known of Indian meteorology as will serve as a groundwork of information for those who may desire to engage in the further study of the phenomena around us. This seems a necessary addition to the original work, since, in many respects, phenomena which are here familiar and striking, are but of subordinate importance in extratropical countries, and *vice versâ.* There are several excellent manuals to which persons may refer who desire to understand something of the science in its European aspects. Among the best are Buchan's Handy-book, and Introductory Text Book, Loomis' Treatise, and Herschell's Meteorology, which, though written many years ago, and therefore in some few respects requiring revision, is still unequalled for thoroughness in a physical point of view. For readers of German, Mohn's Hand-book is an admirable recent work; and among the older works Kaemtz and Schmidt are still valuable works of reference. For a knowledge of the cotemporary progress of the science, the Journal of the Austrian Meteorological Society,[a] edited by Dr. Carl Jelinek and Dr. J. Hann, is an unrivalled source of information.

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[a] Zeitschrift der österreichischen Gesellschaft für Meteorologie.

BAROMETER.

Object and principle.—The barometer is used to measure the pressure of the atmosphere.[a] It has many forms, but consists essentially of a vessel of mercury termed the cistern, in which is inverted a glass tube closed at top and open below, and which, before being inverted, has been entirely filled with mercury. In virtue of the law of fluid pressure; the air pressing on the mercury of the cistern can support in the tube a column of mercury, which presses on its base, with a pressure equal to that of the air on the same area of cistern surface. An air column, resting on the surface of the sea, presses equally with a column of mercury of the same diameter and about 30 inches high on an average. If, therefore, the tube be shorter than this, the barometer being at the sea level, it will remain full of mercury. But if longer, (and a barometer tube always is longer than 30 inches,) the mercury will fall to about that height, leaving a vacuum in the upper part of the tube which is known as the Torricellian vacuum. As the pressure of the air varies, so does the height of the barometric column vary; since, the greater the pressure of the atmosphere, the higher the column it supports in the tube.

2. Verticality.—It is to be observed that the height of the column, here referred to, is the *distance* between the *surface of the mercury in the cistern* and that of the top of the column *measured on a vertical line.* A barometer must, therefore, be perfectly vertical by the plumb line, or its length, as read off on the scale attached to it, will be invariably greater than its vertical height. If a barometer is suspended by a ring at the top, or, as marine barometers usually are, from a gimbal considerably above the centre of gravity of the instrument, it will take the vertical position at once. But if it is fixed at top and bottom to brackets projecting from a backboard (Fig. 2), its verticality must be adjusted by a plumb line.

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[a] Much confused and erroneous reasoning has arisen from persons failing to distinguish between the *pressure* of the atmosphere and its *weight*. The barometer measures its *pressure*; and this is equal to its *weight* (or, more correctly, *static* pressure) only when the air is at perfect rest and undergoing no change of temperature; a condition which, of course, is never completely fulfilled. Probably, on an average, the actual weight of the superincumbent atmosphere is most nearly shewn by its pressure about 4 or 5 in the afternoon and between 3 and 4 in the early morning: but the justice of this view depends on what is the true explanation of the diurnal oscillation of pressure; and it may be said truly that we know nothing accurately of the weight of the atmosphere, but only that it cannot be very different from the average pressure. It is best, in speaking of the barometric condition of the atmosphere, to avoid the use of the term 'weight' altogether, unless there be special reasons for referring to it.

3. Adjustment of Levels.—It has been said that the height to be measured is that between the *surface* of the mercury in the cistern and the top of the column. Now, the top of the column is not flat, but a curved, convex surface (except in very large tubes). The line which bounds the contact of the mercury with the glass is appreciably lower than the real surface, and must not be taken as the measure of the height. This is very often done by persons unacquainted with the proper use of the instrument, but readings so taken are of no value for any scientific purpose. *The measurement must always be taken from the highest point of the curve.* This is effected by means of the vernier, which will presently be described.

Since the quantity of mercury in a barometer is constant, if the column rises in consequence of increased atmospheric pressure, some mercury must enter the tube from the cistern, and the level of the latter falls. The total change, therefore, is made up of the rise of the column added to the fall of the cistern level, and this is measured by various contrivances.

4. Fortin's Principle.—By adjusting the cistern level to a constant point, which is the zero of the scale. This is called Fortin's principle, and is that most commonly adopted. Barometers constructed on this principle have the bottom of the cistern formed by a bag of leather (see Fig. 1) or a solid, but movable piston. A screw, provided with a milled head, projects from the bottom of the brass casing which encloses the cistern. By turning this screw, the bag or piston is raised or lowered, decreasing or increasing the capacity of the cistern, and, as a consequence, raising or lowering the mercury. The upper part of the cistern is of glass, which renders visible the surface of the mercury, and also a pointed or a chisel-shaped stud which projects from the cover, and the lower end of which is the zero point of the scale for measuring the column.

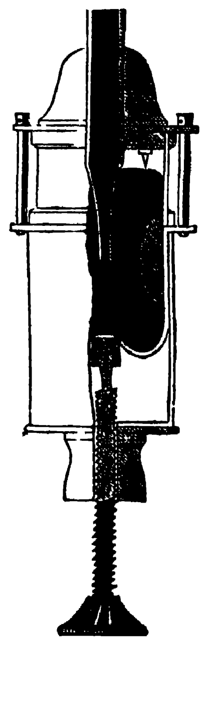

Figure 1. Barometer cistern on Fortin's principle, partly in section to shew the construction.

To adjust the cistern level, first lower the mercury, by turning the screw until the surface is well below the stud. Then raise it again very slowly until it just touches the point of the stud without being indented. If the surface of the mercury is bright, the moment of contact may be

judged very accurately, by watching the apparent approach of the point and its reflection until they meet. If the point appears to indent the mercury surface, the latter is too high and must be lowered.

If the stud have a chisel edge, the adjustment may be determined by so screening the cistern at the side, that the ivory stud is well shaded; and keeping the eye on the level of the mercury surface, looking beneath the knife edge towards the light, or, better, towards a piece of paper or other white surface behind. A streak of light is then seen below the stud until the instant that contact is made, when it at once disappears. The degree of accuracy with which the adjustment may be made very much depends on the skilful arrangement of the light (see § 17).

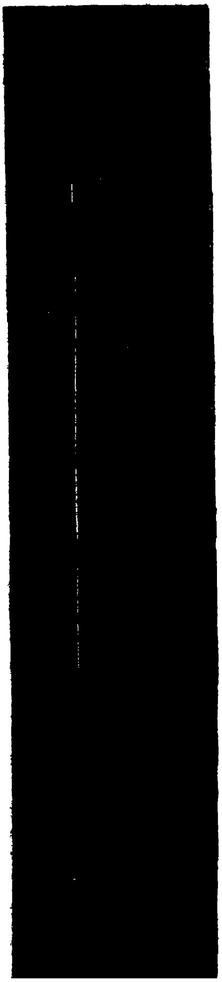

Figure 2. Newman's Standard barometer.

5. **Newman's Standard.**—In this form of barometer, the cistern capacity is constant, but the scale is movable. The graduated part of the scale does not exceed a few inches (26 to 31 inches) opposite the upper part of the column, and a metal rod, attached to the back of the scale and concealed in the hollow frame of the instrument, terminates below in an ivory point (9 in Fig. 2), which is the zero of the scale graduation; the rod and scale are raised and lowered by means of a pinion at the side (8), working in an endless screw, and the zero point of the scale is thus adjusted to the cistern level.

6. **Double reading.**—This principle is adopted in the syphon barometer, and also in some large observatory standards, and several other forms of barometer. The scale is fixed, and the cistern level cannot be adjusted; but the variation of the latter, above or below a certain fiducial level, which is the zero of the scale, is measured by a small independent scale, and this is added to, or subtracted from, the reading of the column.

7. **Capacity correction.**—This may be applied to any barometer, provided the internal diameter of the tube and that of the cistern, or their ratio, are accurately known; and, although its use involves a little extra trouble, it has the advantage of being less liable to error (in the case of individual readings) than any of the mechanical methods above described, the accuracy of which much depends on the observer, the state of the instrument, the arrangement of the light, &c. Nothing can be more

simple than the capacity correction both in principle and practice. Suppose both the tube and cistern of the barometer are perfectly cylindrical, the internal diameter of the former being d, that of the latter D; and let the *external* diameter of the tube, when it plunges into the mercury of the cistern be δ; then, other things remaining the same, if mercury enters the tube from the cistern, increasing the column by a height h', the fall in the cistern level will be $h' \frac{d^2}{D^2-\delta^2}$, since these heights will be inversely as the surfaces that rise and fall, or as the squares of the diameters of the tube and cistern. Suppose that, at a particular reading, H, the zero of the fixed scale is exactly coincident with the cistern surface of the mercury, and is therefore correct: this is called the *neutral point* of that instrument. If, then, we take a reading higher than H (say $H+h'$), we must add the quantity $h' \frac{d^2}{D^2-\delta^2}$. If lower than H (say $(H-h')$, we must deduct the corresponding quantity, in order to obtain the true reading. Suppose, for instance, a barometer is known to give a true reading at 29 953 (when the reading has been reduced for temperature in the manner presently to be explained). The internal diameter of the tube at the top of the column is 0·34 inch and that of the cistern 1·62 inches: the external diameter of the tube, where it enters the mercury of the cistern, is 0·30. Then, a reading which, after reduction for temperature, gives 29·764 inches, is to be corrected as follows:—

Uncorrected reading	29·764
Deduct neutral point H	29·953
Difference h'=	—0·189

$$\frac{d^2}{D^2-\delta^2}=\frac{0{\cdot}34^2}{1\,62^2-0\,30^2}=0{\cdot}046 \text{ nearly, and}-0{\cdot}189\times0{\cdot}046=-0\,008694 \text{ or}-0{\cdot}009 \text{ nearly,}$$

which, applied as a correction to the original reading, gives 29·764 —0·009=29·755, the true reading. The factor 0·046 is constant for the same instrument, so long as the same tube and cistern are in use. The neutral point H, is also constant, so long as there is no loss of mercury, and the relative position of the scale and other parts of the instrument are unchanged: but if any mercury is lost by leakage, the neutral point will be lowered, and if a new tube has to be fitted, both the neutral point and the factor for capacity are altered and must be redetermined.

8. Kew principle.—In the foregoing description it was shewn that the rise or fall of the column h', as measured on the scale, represents a larger change, *viz.*, in the example given $h'(1+{\cdot}046)$. If then, in such a case, the scale be so divided that each *real* inch is made to *represent* 1·046 inches, or, in other words, if the inch represented on the scale

really measures $\frac{1}{1\cdot046} = 0\cdot958$ inch only, the scale, if true at any one position of the column, will be true for all other heights, and no correction will be required, and no adjustment of the cistern or scale. On the other hand, any index error will be constant, and the same for every part of the scale. This is termed the Kew principle. Its adoption saves some trouble; but if the tube of a barometer of this construction be accidentally broken, another tube of exactly the same diameter must be substituted, or a capacity correction must be computed and applied to the readings; and the determination of this correction, in the absence of a vacuum chamber, is tedious and troublesome; especially in India.

9. Use of the vernier.—The use of the vernier is to facilitate the accurate measurement of the height of the column. Each inch on the fixed scale of a barometer is generally divided into tenths and half-tenths of an inch, written 0·1 and 0·05. If, now, a length equal to 24 or 26 of these latter sub-divisions be set off on an independent movable scale and divided into 25 parts, each of these latter sub-divisions differs from a scale sub-division by $\frac{1}{25}$th of itself, being in the one case less, in the other greater. Such a scale is called a vernier. Now, let the vernier and fixed scales be applied to each other, edge to edge, as in Figs. 3 and 4. If the first mark of the vernier coincide with a mark of the fixed scale, the last will coincide also, but no other, and in all other cases only one mark of the vernier will coincide with a scale mark. Since each vernier division is $\frac{1}{25}$th greater or less than a scale division, the number of vernier divisions between the coinciding mark and the zero of the vernier will shew how much this zero deviates from the scale mark next below it. If the vernier scale is equal to 24 sub-divisions of the fixed scale, it reads upwards in the same direction as the fixed scale (fig. 3); if to 26 divisions, it reads downwards *from its own zero* (fig. 4).

The vernier scale is usually engraved on a piece of metallic tube which may be moved up and down, either directly by hand, or by means of a pinion and rack. [10 fig. 2.] In taking a reading, the lower edge of this tube* must be made to coincide accurately with the top of the mercurial column, as shewn in the annexed woodcut, and this requires that the top of the column shall be exactly on the same level as the eye of the observer. [See fig. 5.] In this position, on looking through the tube, the lower edges of the vernier slide in front and behind will coincide. To set the vernier then, raise it a little above the top of the column, get both edges in a line with the eye, and then lower it slowly till these edges form a tangent to the topmost outline of the column, no part of it being covered. If the zero line of the vernier is the lower edge of the slide and coincides

* In some verniers which read downwards, a part of the vernier slide is cut away and the upper edge of the opening, which is frequently bevelled off, marks the zero of the vernier.

exactly with one of the fixed scale divisions, that division gives the reading. If not, take as the scale-reading the division next below the edge of the vernier, and add thereto the reading of the vernier.

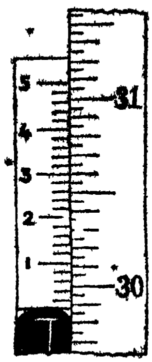

Figure 3.

The vernier bears five principal divisions, the value of each being one-fifth of the smallest *scale* division, therefore =0·01; and each of these has five sub-divisions or parts = 0·002. The annexed woodcuts will illustrate the use of the vernier. In fig. 3, the lower edge of the vernier intersects the scale above the division 29·85 and below 29·9. Write down 29·85 as the scale reading. Then, running the eye up the vernier, the third of the major divisions is seen exactly to coincide with a scale division. Its value 0·03 added to 29·85 gives 29·880, which is the exact reading.

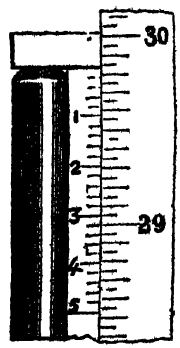

Figure 4.

In fig. 4, the lower edge of the vernier gives the scale reading 29·8, being above 29·8 and below 29 85. The vernier mark, which coincides with a scale mark, is the fourth beyond the vernier division marked 2, and has therefore the value 0·028. Adding this to 29·8, the exact reading 29·828 is obtained. Finally, if neither of the vernier marks exactly coincides with a scale mark, but one is a little above, the other a little below a scale division, ·001 is to be added to the reading of the lower of the two.

As a final caution it may be mentioned that, if the barometer is so suspended that the top of the column is above the eye of the observer, or if the eye is above this level, so that the front and back edges of the vernier cannot be made to coincide, the reading will invariably be *too high*. This

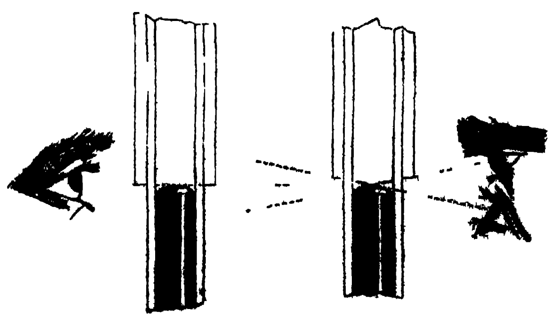

Figure 5. Effect of parallax.

is owing to parallax, and is illustrated by the accompanying figure (fig. 5). The vernier *appears* to be set when its lower edge forms an apparent tangent to the meniscus of the mercury surface. If the eye be too low, the hinder edge of the vernier slide will appear to do this before the vernier is lowered to the same level; if the eye is above the top of the column, the front edge will do so. But the front and back edges of the vernier will coincide with each other, and with the mercury surface, only when all three are on the same level. Before taking the reading, the setting of the vernier must, therefore, always be verified by moving the eye up and down; to ascertain, *1st*, that in no position of the eye is light seen between the highest part of the surface and the edge of the vernier; and, *2nd*, that there is one position in which the vernier conceals no part of the mercury meniscus, but only touches it.

10. Method of Reading.—First observe and write down the temperature of the thermometer attached to the barometer [11 fig. 2]. Then, (in the case of a barometer on Fortin's principle,) adjust the cistern level by turning the cistern screw till the fiducial point is quite free of the mercury, and then raising the latter till contact is made. [§ 4]. Next, adjust the vernier, by raising it till it is well above the top of the column, and then lowering it till the back and front edges coincide exactly, and form a tangent to the meniscus or curved surface of the top of the column, without covering any part of it. Note down the reading, and, having written it down, verify it by another reading of the scale and vernier. Lastly, re-observe and verify the temperature of the attached thermometer.

If the barometer be one with a narrow tube, such as a marine or mountain barometer which acts slowly, the tube (or scale) should be gently tapped with the finger-tips before setting the vernier, and again after the first reading, when the vernier should be re-set. This should be repeated till further tapping produces no further change in the reading.

11. Capillarity and Friction.—The reading of the barometer does not give at once the true pressure of the air. The mercury has no such attraction for glass as water has, and does not wet it; and in rising in a glass tube, it has to overcome a resistance due to the cohesion of the mercury, which prevents its reaching the full height at which its weight alone would counterbalance the atmospheric pressure. This deficiency is the *greater* the *smaller* the bore of the tube; and conversely, becomes less as the diameter of the tube is greater. The deficiency is constant for the same tube, and can therefore be expressed by a number which holds good for all readings of that tube. This number is termed the *capillarity correction*, and is often engraved on the brass scale of the barometer. It is to be *added* to the reading. In small tubes, the deficiency is always greater when the barometer is rising than when it is falling. This difference is owing to friction.

12. **Index error.**—Sometimes the capillarity correction is not given separately, but is combined with another constant correction, *viz.*, that of the scale. This correction is always small in barometers of modern manufacture by good makers. It is for the slight error of the graduation. The lines marked on the scale *should* represent standard inches when the brass of the scale has a temperature of 62° Fahr. Any slight deviation from this amount is termed the "index error," and is to be added to, or subtracted from, the reading, according as the graduation is greater or less than the true amount.

The capillarity and index corrections are to be made to the readings *first of all.*

In practice, the total error for scale and capillarity are usually ascertained by comparing each instrument, either directly or indirectly, with the standard barometer of some well-known public observatory (not with any instrument that may be called 'a standard'). In Bengal and Northern India generally, the barometer by Newman, No. 86, which is the standard of the Surveyor-General's Office in Calcutta, has for many years past been used as the general standard of reference, and the readings of all barometers are corrected to and made comparable therewith. This has been ascertained to read 0 011 inch higher than the Kew standard, and 0·013 higher than the Greenwich standard; therefore the correction of any instrument to the Calcutta standard is ·011 higher than to the Kew standard.[a]

The registers of a barometer, whose correction to some well-known public standard is unknown, are of very little use until that correction shall have been ascertained and applied. They may serve to shew the changes of pressure at the place itself; but these, taken by themselves, are of little value. In discussing any question of physical meteorology, we require to know the pressure at the place relatively to other places, and it is obvious that this comparison can be made only by reducing all to one common standard. The differences thus to be dealt with are very

[a] From the results of a comparison made by Captain Rikatcheff, I. R. N., and published in the Proceedings of the British Meteorological Society, vol III, p 248, I have deduced the following corrections of the standard barometers of some of the principal Observatories in Europe to the Kew barometer—

	Inch.		Inch.
Paris	—·006	Stockholm—	
Brussels	—·014	Royal Academy of Science	— ·003
Utrecht	—·018	Upsala	+ ·004
Munich	—·010	Copenhagen—	
Berlin (Prof. Dove)	— ·010	Academy of Agriculture	— ·015
St. Petersburg—		Christiania	+ 0·14
C.P. Observatory	+ ·008		
Pulkowa	+ ·017	Calcutta	— ·011
Imperial Academy	—·004		

small in the tropics; and in comparison therewith, barometric errors are in general too large to be neglected.

13. Comparison of Barometers.—To ascertain the difference of two barometers, it is not enough to take one or two readings only. The number of readings required will depend on the care and accuracy with which they are taken; but they must be sufficiently numerous and varied in condition to eliminate those irregularities which arise from inequality of temperature in the parts of the instruments, inequality of action arising from friction, &c. A careful and skilful observer should take at least 20 readings of the two instruments simultaneously, half with a rising, and half with a falling, pressure; and either at such times as the temperature is steady, or at all events when it is changing but slowly; less skilled observers should take double or treble that number of readings, under the conditions specified. Every reading is then to be reduced for the temperature reading of the instrument itself (see next §); all readings should be rejected, the differences of which greatly exceed or fall short of the average of those taken under similar conditions, and the mean difference of the remaining readings will give the mean error.

During the comparison the barometers must be suspended with their cisterns at the same level, and care must be taken that they are vertical, and with the top of the column not above the observer's eye.

14. Correction for Temperature.—In reading a barometer, we measure the length of a column of mercury by means of a graduated scale usually made of brass. Both of these are subject to expansion and contraction, with every change of temperature. Were no correction made, the mercurial column, with every increase of temperature, would rise (or lengthen), and indicate an increased atmospheric pressure without any such change really having taken place. On the other hand, the brass rod, also expanding, would become longer than its graduation indicates, and therefore the mercurial column (as measured by it) would seem shorter than it really is. Thus, the two errors partly neutralize each other. But each inch of mercury expands 0·0001001 inch for every degree Fahr., while brass expands only 0·00001043 inch for each degree. Therefore, the expansion of the mercury is nearly ten times greater than that of the brass.

It has been said above that the brass scale is so graduated as to read standard inches at 62° Fahr. It is, however, at the temperature of 32° that barometric readings are supposed always to be made, and, therefore, it is to this latter temperature that all barometric readings are reduced.

This calculation is made by the formula*—

$$h = l\,\frac{0{\cdot}0001001(t-32)-0{\cdot}00001043(t-62)}{1+0{\cdot}0001001(t-32)}\,.$$

* Let h be the real height of the barometric column (reduced to 32°), l the reading of the scale, t the Fahrenheit temperature, β the co-efficient of volumetric expansion of the

when l is the observed reading of the barometer; t the observed temperature of the attached thermometer, and h the quantity to be deducted from l to reduce the latter to the freezing point value required.

Table I is thus calculated; the figures at the top of each column are different values of l: those at the side columns are the different values of t.

The method of using this table is fully explained in the remarks which preface the Tables.

15. Reduction to Sea Level.—Since the pressure of the air at any elevation depends chiefly on the mass of the atmosphere above its level, the higher the barometer is carried, the smaller the pressure it indicates, and its readings are frequently used to measure the height of mountains, &c.; *viz.*, by computing the height of the column of air, the weight of which is equal to that of the column of mercury, whose height is given by the difference of the barometric readings at the top of the mountain and at sea level. Conversely, if our object be to compare the pressures of the atmosphere in different parts of a country or of the globe, with a view to discovering those differences which are effective in producing winds, we must eliminate all differences due to the varying elevation of the places of observation. The most convenient mode of doing this is to reduce all to their equivalent values at sea level.[a]

Various formulæ and tables computed therefrom have been given for this purpose, and will be found in Boileau's tables, Guyot's tables, and many other publications. A very convenient table, sufficiently accurate for all ordinary purposes and very simple in use, has lately been computed and published by Captain Allan Cunningham at Roorkee. For heights below 500 feet, that given in the accompanying collection of tables (Table II) gives a sufficiently close result and is the simplest of all in application.

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mercury, and α the co-efficient of linear expansion of the metal of the scale, for one degree Fahrenheit. Then, since the reading l of the scale is true at the temperature of 62° Fahr. at $t°$ it becomes $l\,[1 + (t-62)\,\alpha\,]$ and this is equal to the height of the mercurial column at the same temperature Therefore we have—

$$h\,(1 + (t-32)\,\beta) = l\,(1 + (t-62)\alpha)$$

$$\therefore h = l\,\frac{1+(t-62)\,\alpha}{1+(t-32)\,\beta}$$

$$\text{and the correction } (l-h) = l\left(1-\frac{1+(t-62)\,\alpha}{1+(t-32)\,\beta}\right)$$

$$= l\,\frac{(t-32)\beta-(t-62)\alpha}{1+(t-32)\,\beta}$$

[a] There is a limit of elevation beyond which it is useless to reduce observations to sea level; because the reduction has no real physical meaning. Thus, at hill stations 6,000 or 7,000 feet above the plains, the pressure is that of a stratum of the atmosphere, in which the relations of pressure are, at certain times, demonstrably different from those on the plains below. The reduced pressures of these stations are, therefore, not comparable with those observed on the plains.

All these formulæ, however, assume certain conditions of temperature and vapour distribution, which, since these elements are subject to incessant disturbance, scarcely ever represent the actual state of the atmosphere at any given moment, though they may be approximately true on the mean of a large number of observations. The results, therefore, can be considered true for individual observations, only when the reduction is made for small heights, such as places on the lower part of the Gangetic plains; and the probable error increases with the elevation. This error is the more nearly eliminated, the larger the number of observations from which the mean result is obtained for the reduction.

16. Determination of Level.—A barometer, which at the sea level stands at 30 inches, falls, on an average, ·001 inch for every foot of elevation for the first 800 feet, when the air has a mean temperature of 90°; and by a greater amount for all lower temperatures. Since a barometer is read and corrected to the nearest thousandth of an inch, it is therefore necessary, in order to correct it truly for elevation, that the height of the mercury surface of the cistern above mean sea level should be ascertained (if possible, by spirit levelling), to the nearest foot. The elevation of the station, as given, for instance, on a map, is therefore insufficient for the purpose; and every pains must be taken to obtain the real level of the barometric cistern as accurately as possible. In most large stations of India, the elevations of certain bench marks have been fixed by spirit levelling; and, wherever such is the case, it is necessary only to run a line of levels from the bench mark to the barometer. It follows, of course, that if the barometer is moved to another place, the difference of level must be determined in the same manner, and, until this has been done and the resulting correction applied, the readings taken before and after the removal are not comparable with each other. *A very large proportion of the barometric registers hitherto kept in India are of little or no value, owing to the neglect of this precaution.* The effective differences of pressure in different parts of India are so small, that the reduced barometric values are rendered seriously misleading by errors of a few feet in the assigned elevation.

The elevation of stations to which no line of spirit levels has been carried, and which are not sufficiently near any Great Trigonometrical Survey station to allow of a line of levels being carried to it, may be obtained approximately by the barometric readings, *if all other corrections have been duly applied.* But for this purpose it is necessary, *first*, that the mean of several years' observations at the station are available for comparison; and, *second*, that the comparison can be made with series simultaneously recorded at, at least, three or four stations, lying in different directions around, and not at too great a distance; all these having equally been corrected to one and the same standard. Single observations,

and even short series, are quite insufficient for the purpose, especially if the elevation to be determined is considerable. Even with all precautions, such determinations can never have the trustworthiness of those obtained by the spirit level, for they proceed on the assumption that, in the long run, the pressure is the same at all the places *compared* when reduced to the same horizontal plane; and it is known that this is not the case in fact. There are, or may be, permanent differences of average pressure between different parts of the one and the same country. Barometric determinations of level are, therefore, to be resorted to only when more trustworthy methods are inapplicable.

17. Position of a Barometer.—A barometer, unlike a thermometer, *must be exposed as little as possible to changes of temperature.* The justness of the temperature correction depends upon all parts of the instrument having the same temperature as that shewn by its attached thermometer. But the mercurial column is inclosed in a glass tube, a bad conductor of heat, and this again usually in a metal tube, with an air space between. Consequently, the mercury is slow in acquiring or parting with heat; and it is only by keeping the temperature around as uniform as possible that the required conditions are even approximately fulfilled. *A barometer should, therefore, be kept in a well-enclosed room and the sun must never shine on it; nor must it be near a fire-place.*

The second point to be attended to is to obtain a good light, since the accuracy with which the instrument may be read much depends on the lighting. The source of light should be either on right or left hand; (not from the back, and still less from opposite the barometer). And a white surface, well illumined, should be provided behind the cistern, and also the upper part of the tube, to facilitate the accurate adjustment of the mercury level and the vernier.

If a barometer is provided with a back-board, a piece of white paper, about the size of a lady's visiting card, should be pasted behind that part of the tube at which the readings are taken, and another piece behind the cistern.

For barometers without back-boards, small card clips [Fig. 6] are now constructed at the Mathematical Instrument Manufactory in Calcutta, which can be attached to the instrument, with a clean white card C inserted. This is the best kind of reflector that can be employed. It is adjusted somewhat more obliquely than as shewn in the figure; so as to reflect the light from the right or left of the instrument.

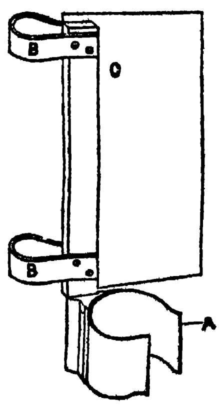


Figure 6. Card clip for barometer.

It has already been pointed out that *a barometer must be perfectly vertical,* and so hung that *the top of the column is not above the level of the observer's eye.* It may not be superfluous to add that *it must be kept clean,* and that the exposed part of the tube and cistern glass require occasional wiping (with a damp cloth if necessary).

A barometer should never be moved from the place it has habitually occupied, except such removal is absolutely unavoidable.

18. Tests of condition.—When a barometer is in good order, if slowly inclined till the mercury touches the top of the tube, it gives a sharp click at the moment of contact. If it fails to do this, there is air above the column. The surface of the mercury against the tube should be bright, and there should be no visible air specks. A dull surface shews that there is probably a film of air adhering to the glass. Air is, however, injurious only when it reaches the Torricellian vacuum above the column.

Sometimes little drops of mercury form by condensation on the inner surface of the tube in the Torricellian vacuum. They do not affect the reading and are of no importance.

If a barometer on the Fortin principle is found to have leaked a little at the cistern, it does not affect the reading, so long as sufficient mercury remains to admit of the mercury level being adjusted to the fiducial point. But if it continues to leak, it should be dismounted and put aside in an inverted position until it can be sent for repair; *but any leakage whatever in a barometer to which a capacity correction is applied, or one on the Kew principle, introduces a permanent error, which affects all its readings.*

19. Packing and carriage of barometers.—A barometer must always be packed and carried in an inverted position, that is, *cistern upwards,* (or else horizontal.) The safest mode of packing is to construct a dooly of bamboo of the form shewn in the annexed figure, [*Fig.* 7]; and to lash the barometer to it in the proper position and well surrounded by straw. The whole may then be covered with canvas or gunny cloth, leaving a hole for the insertion of a bamboo beneath the forks, by which it is to be carried by two coolies in the manner of an ordinary dooly. Such a package may be sent safely by rail or ship, provided ordinary care be used in placing and moving it. If a barometer is on Fortin's principle, before packing it, the cistern screw should be

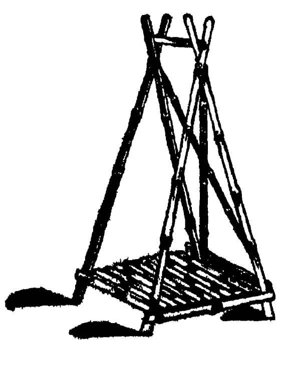


Figure 7. Dooly for carrying barometers.

turned till a small air space only, (about as large as the bowl of a tea spoon,) is left in the cistern.

20. Selection of a barometer.—In the hands of a practised observer, a barometer on Fortin's principle is the most convenient. The best yet tried in the observatories of the Meteorological Department are the Newman's large standards, and the small standards constructed by Casella, which latter have a leather bag at the bottom of the cistern. Some makers have, of late years, substituted for this bag, a solid glass piston working through a leather collar; these have been largely tried, but they are so subject to leakage as to be quite unfit for the dry climate of the interior of India.

The chief objection to Fortin's barometer is the liability of the mercury to oxidise; but, when the mercury is carefully purified, it may be kept in good condition for many years. The cistern is easily opened and the mercury removed and cleaned by any person accustomed to the manipulation of such instruments; but it should not be attempted by the unskilled.

The oxide is removed by passing the mercury through a filter made of a cone of writing paper with a pin hole at the apex. The cistern must be wiped out with a clean cloth before the mercury is returned. If, however, the mercury contains foreign metals dissolved in it, it must be purified by chemical means or must be re-distilled.

Newman's standards are also excellent barometers. There are many of them in use in India, and with proper care they stand well in all climates; but they are costly, and heavy in transport.

For stations at which the observers are less skilled, small standards on the Kew principle are best fitted. Marine barometers on the same principle may also be employed, but many of them are slow in action, and they fail to shew the full daily range of pressure.

Barometers with wooden cases, such as those used in most ships, and such as are set up in the halls of private dwellings, are not fitted for the purposes of scientific observation, and the words "change," "fair," "set fair," &c., frequently marked on them are meaningless and misleading in India. The remarks engraved on Fitzroy's barometers are scarcely more applicable in Bengal.

21. Aneroids.—For meteorological purposes, aneroids cannot be trusted in India, unless they can be compared frequently with a mercurial barometer as a standard of reference. The delicacy of their machinery renders them very liable to derangement in transport, and there is much difficulty in ascertaining their temperature correction. They are useful for rough hypsometrical observations, and that is their chief use.

THERMOMETER.

22. Principle and construction.—A thermometer is an instrument for measuring the temperature or warmth of the air or other medium, by means of the expansion of a fluid enclosed in a glass bulb. Nearly all fluids expand and occupy a greater space when warmed, but that used for thermometers is usually either mercury or spirit of wine. It quite fills the bulb and extends some distance up a fine tube opening into it; and, as the bore of the tube is very small, a very small change in the volume or bulk of the fluid is made perceptible by its extension or regression in the tube.

23. Principle of graduation.—There are two fixed points of temperature obtainable without much difficulty, and with great accuracy; *viz.*, that at which ice melts, and that of the steam given off by boiling water at London, when the barometer reduced to the freezing point stands at 29·905 inches.[a] The difference of these temperatures on the thermometers in general use in England, India and most English-speaking countries, is divided into 180 parts, termed degrees; and the lower temperature being called 32°, the higher becomes $32° + 180° = 212°$.

24. Meaning of degrees of temperature.—In graduating standard thermometers, the tubes, when filled, are immersed first in melting ice, and then in the steam of boiling water, and marks are made on the tube to indicate the points at which the fluid stands in the two trials respectively. The interval is then divided into 180 parts. A number of similar, equal divisions are afterwards set off below the freezing point, and the 32nd is termed 0°. Thus, it will be understood that degrees are purely conventional divisions; and not only *might* the interval between the melting point of ice (commonly termed the freezing point) and the temperature of steam (as above defined) be sub-divided into any other number of parts than 180, but two such other systems of sub-division are very widely employed. That just described is termed the Fahrenheit scale, and is generally used in England and America; another, used almost exclusively in France, and by chemists and physicists of all countries, and termed the Celsius or centigrade scale, has 100 degrees between the freezing and boiling points[b]; and the former is termed 0°, the latter 100°; and in Germany and Russia the same interval is generally divided into

[a] This pressure would be equal to 29·924 ins. at Calcutta.

[b] The boiling point of the centigrade scale, though very nearly, is not accurately the same as that of the Fahrenheit scale.—See Balfour Stewart's *Elementary Treatise on Heat*, p. 129.

80 parts, the freezing point being 0°, and the boiling point 80°. This is termed Reaumur's scale.

25. Scales.—The tube, bulb, and scale are the essentials of every thermometer; but the scale is often engraved on the tube, and sometimes no other scale is attached; thermometers used by meteorologists, except radiation thermometers [§ 45], generally have, however, an attached scale as well, which is especially made to correspond to the graduation on the tube. Consequently, a scale is of use only for that particular tube for which it has been engraved.

26. Errors and corrections of thermometers.—Although there has been a great improvement in the manufacture of thermometers of late years, still very few instruments are free from error, and none can be *assumed* to be accurate. The causes of error are various. In the first place, the bore of the thermometer may be not quite equal throughout, in which case equal divisions on the scale will not correspond to equal increments of expansion of the fluid; or the graduation itself may not have been quite accurate; and, secondly, as the glass of the bulb undergoes a slow contraction for some years after the instrument has been made[a], it is generally found that, after a lapse of time, the thermometer gives too high a reading in all parts of the scale. Errors, thus arising, not infrequently amount to a degree, or even more, especially in the case of spirit thermometers, the ratio of expansion of which fluid does not accord with that of mercury; and, consequently, every instrument should be tested and its errors determined at different parts of the scale, and the corresponding corrections should be applied to all its readings.

27. Comparison of thermometers.—It would be too tedious to eliminate the errors of thermometers for ordinary observation by absolute methods. It is sufficient if the freezing point be verified by immersing the thermometer in crushed melting ice, and if a comparison be made with a good standard thermometer, (the errors of which are known) at four or five higher temperatures, such as divide and comprehend the range through which it is intended to register. But to do even this much satisfactorily requires some practice and certain proper appliances; and it should always be performed at a depôt or central observatory before the instrument is issued. A comparison may, however, be made, without much difficulty, at and near the temperature of the place, by removing the attached scales of the thermometers to be compared, and immersing the tubes in water in the positions with which they are ordinarily

[a] A thermometer, in the possession of Prof. Joule of Manchester, was found by him to be still undergoing a progressive rise of the freezing point, after 29 years from the time of its construction. The total rise in this time was a fraction less than 1 degree Fahrenheit, more than half of which took place in the first four years.—See *Proceedings of the Literary and Philosophical Society of Manchester*, vol. XII, page 73.

read; *i. e.*, if, like most self-registering thermometers, their suspension is horizontal, they must be immersed horizontally in the water and so read. This is chiefly important with mercurial thermometers. If this be impracticable, the thermometer may be tested in the vertical position, and afterwards, when it has acquired the temperature of the air, or is immersed in a broad vessel of water of uniform temperature, it may be read in both positions and the difference added to the error. The comparison may be extended in this manner to a moderate distance, (10° or 15°) above and below the actual temperature; the water being stirred meanwhile to ensure a uniform temperature. But the greater the difference, the more difficult is it, by such means, to ensure uniformity of temperature, and therefore, a trustworthy result, if one instrument is much slower than the other in undergoing changes of temperature.

A comparison of thermometers suspended, side by side, in the air, when the temperature is subject to rapid changes, is of little or no use, unless protracted over a long period, during which a great number of readings are recorded with a rising, and an equal number with a falling temperature. Even then a mean error only is obtained, whereas the comparison in water gives the variation of the error at different parts of the scale.

The standard should be either one graduated, calibrated and otherwise verified at the Kew observatory, or a thermometer that has been thoroughly compared with such a Kew standard.

The errors of thermometers, however small, cannot be considered as trivial and negligible. Even though it may be the observer's practice to neglect all fractional parts of a degree in reading his thermometers, an error of only 0·1° will still appear in the mean of a large number of such readings, on comparing it with the mean reading of a standard recorded simultaneously; and in many investigations, such as, *e. g.*, the effect of lunar heat, and, even in comparing the mean temperatures of successive years, an error of one or two tenths of a degree appreciably affects the result.

28. Precautions in reading thermometers.—To read a thermometer accurately requires some little care.

1st.—The eye must be exactly at the level of the reading, if the thermometer is vertical; and, in all cases, must be so situated, that a line drawn from the eye to the top of the column would cut the axis exactly at right angles. The reason for this precaution is the same as that already given in the case of the barometer. If the eye is above the reading, however little, the reading will be too high; and *vice versâ*. This is a point frequently neglected by careless observers.

2nd.—The thermometer must be read quickly, and the face and head must not be very near it; otherwise, it will be affected by the warmth radiated from the body.

3rd.—It must be read to the nearest tenth of a degree by estimation. There is no difficulty in this, and to neglect it is a mark of a careless observer.

4th.—Spirit thermometers are read to the lowest part of the concave surface of the column, mercurial thermometers to the top of the convexity.

29. Varieties of thermometers.—Several variations are made in thermometers intended for special purposes. The principal of these requiring notice are—

The standard (dry bulb)	...	For taking the temperature of air at the moment of observation.
Maximum thermometer	...	For registering the highest temperature attained in the day or other period.
Minimum "	...	For registering the lowest temperature attained.
Solar radiation thermometer	...	For measuring the highest temperature of equilibrium in the sun's rays, when the surrounding objects are constant.
Grass " "	...	For measuring the cooling of air in contact with the earth's surface at night.

30. The standard thermometer (dry bulb).—This is the simplest form of the instrument, and requires no description beyond what has already been given. It is graduated with care, and, when the other thermometers have not been separately verified, serves as the standard with which these others are compared. But a matter which requires great consideration is, 'how to place the instrument so that it may shew truly all changes in the temperature of the air.' And this requires that a few words be said about the mode in which heat acts on the thermometer. These remarks apply equally to the ordinary maximum and minimum thermometers, and to the hygrometers presently to be described.

31. Precautions in placing thermometers.—A thermometer suspended in the air is affected by heat, which reaches it in two different ways; *firstly*, by the contact of the air actually around and bathing the bulb, and the temperature of which is to be measured; and, *secondly*, by heat which is given off from all solid and other objects around, at all times, in all directions, which travels through air and space with the same velocity as light, and, like light, passes freely through some bodies, is absorbed by others, and is reflected by polished metallic surfaces. This last is termed *radiant heat* or, more properly, simply *radiation.* Now, when the object is to ascertain the temperature of the air, the influence

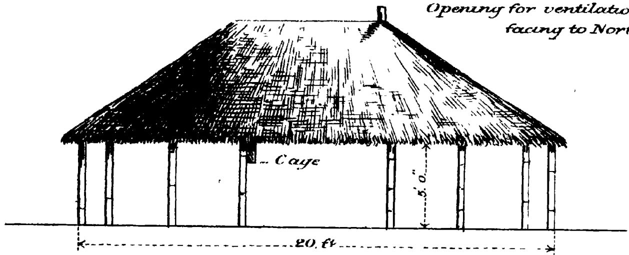
of changes in radiation must be got rid of as much as possible. But it is impossible so to place a thermometer that it is uninfluenced by radiation; for, if even it be screened from the heat radiating from surrounding objects, (which may be effected to a great extent,) it will then radiate off its own heat faster than it can be warmed by the air; and will equally fail, therefore, to show what is required, *viz.*, the temperature of the air.

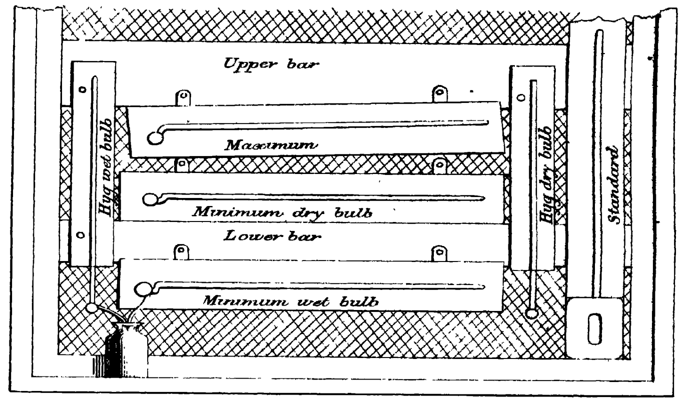
32. Joule's apparatus.—The alternative, then, is to place the thermometer in such a position that the effects of radiation and air-temperature combined may be as nearly as possible identical with those of the latter alone. An arrangement which attains this object accurately has been contrived by Mr. Joule. It consists of a cylindrical copper vessel surrounding a wide tube of the same metal, which is open at both ends. In the axis of the tube is suspended, by a filament of unspun silk, a very light spiral of metallic wire, which carries a small light mirror above the orifice of the tube. The least current of air passing up or down the tube turns the spiral, and the motion is indicated by a ray of light reflected from the mirror. If there be the smallest difference of temperature between the tube and the air around, such currents will be set in motion, so that, when the spiral is motionless in the open tube, this is an indication that there is no such difference of temperature. The temperature of the tube is regulated by filling the cylindrical vessel with water, immersed in which, an accurate thermometer shews the degree of its temperature.

33. Sling thermometers.—An admirable and simple contrivance for obtaining the actual temperature of the air at the time of observation, is that known as the *thermomètre à fronde* or sling thermometer. This is a small thermometer without any attached scale, which is either fixed on a revolving frame, or terminates at its upper end in a glass ring, to which is attached a piece of strong twine about eighteen inches or two feet long. The free end of the string is coiled once or twice round the finger to prevent its slipping, and the thermometer is then swung round five or six times in the air and rapidly read off. The effect of this proceeding is to renew the air around the bulb so rapidly, that any excess of heat received by radiation is lost to the air, and *vice versâ.* It is found that, even in the sunshine, the real temperature of the air may be obtained approximately by the use of this instrument. The temperature of the wet bulb thermometer may be obtained by the same method, but the thermometer should then be swung slowly.

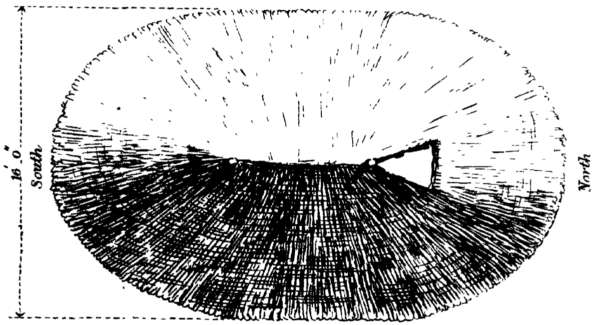
34. Thermometer sheds.—Such an apparatus as Joule's would afford a valuable test of the efficacy of different kinds of exposure, but it is far too delicate for ordinary use. Meanwhile, it has been sought to attain the object in view by shading the thermometer from the sun and sky,

Pl. I.

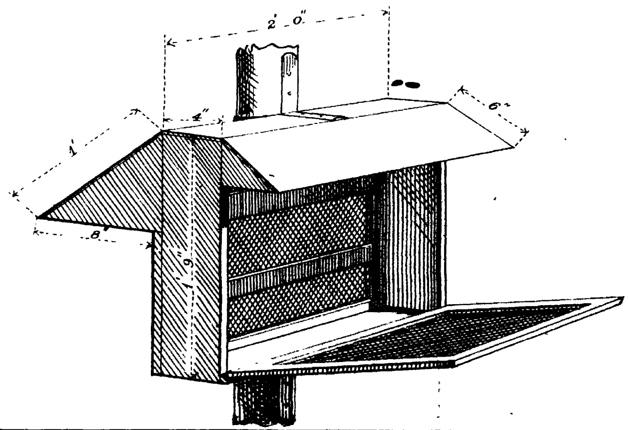




Scale, 2 ins = 1 foot.



THERMOMETER CAGE



S. Sedgfield, Lith. Calcutta

and also from the ground or walls, heated by the sun or cooled by free radiation: exposing it at the same time to the freest circulation of the air. With this view the shed and cage represented in Plate I have been generally adopted in India. The shed consists of a frame-work eighteen or twenty feet long and fourteen or sixteen feet wide, well thatched above and open all round. It should be erected in an open grassy place, at a distance of not less than fifty feet from any wall or other radiating surface, the ridge pole pointing north and south. It has an opening above to allow of the escape of heated air. This opening, however, should be small, and may be advantageously replaced by a section of a large bamboo, to serve as a ventilating pipe, inserted through the thatch immediately beyond the ridge pole. The cage containing the thermometers is affixed to the southern pole and faces to the north. The eaves should be between five feet and five feet six inches above the ground.

35. Objections to verandahs and stands.—Other modes of exposing thermometers are,—suspending them in the verandah of a house, or on an open stand, such as that designed by Mr. Glaisher, or that figured by Colonel James in his well-known "Instructions." Both of these are open to serious objection. The walls of a house absorb a large quantity of heat during the day time and give it out again during the night, while the circulation of air in a verandah is necessarily less free than in an open shed. The result is, that a thermometer thus exposed, shews a temperature too low in the day-time and too high at night. In 1866 and 1867, Dr. J. C. Bow, at Chunar, instituted a comparison between the temperatures shewn by thermometers exposed in a verandah and under a thatched shed; and found that, while in the former position the mean daily range was 12° only, in the latter it was 24° in 1866; and in 1867, 11° in the former and 23° in the latter. Thus, half or more than half of the daily range was lost in the verandah by the want of free exposure. The means for the month and the year were nearly the same in the two cases; but while, on an average, the day temperature was 6° too low, that of the night was by the same amount too high.

On the other hand, the open stand fails to afford sufficient protection against radiation, and in most parts of India the effect of this must be very great. No comparative observations have hitherto been made in India to test its intensity, but it must certainly be far greater than in an English climate; and Mr. Plummer found that, at Durham, the observations of thermometers on a Glaisher stand, shewed a diurnal range of temperature from 2·0° to 8·0° greater than others exposed in a pent-house not very dissimilar from the sheds used in India. Moreover, the Glaisher stand gave a mean temperature 1·3° too high in August, and 0·4° too low in December. There was indeed a difference in the elevation of the thermometers which prevents the comparison being quite satisfactory;

but there can be little doubt that much of the discrepancy observed was attributable to radiation.

36. Maximum thermometer in air.—The object of maximum thermometers is to register the highest temperature attained by the air during the day. This is effected by various contrivances. But it will be sufficient to describe those most in use.

37. Rutherford's maximum.—In Rutherford's (now not much used) the mercury, in expanding up the tube, pushes before it a small porcelain index, which it leaves at the highest point, when the column has reached its limit and contracts on cooling. The lower end of this index, or that touching the mercury, shows the reading. Above it is a small steel pin which, like the porcelain index, moves freely in the tube.

The thermometer is to be re-set after an observation has been recorded. This may generally be effected by simply placing the instrument upright (bulb downwards), when the index will drop to the mercurial column. If it does not, it may be dragged down by applying a small magnet to the steel pin above it and pulling the latter down by the attraction of the magnet. A magnet is furnished with the instrument for this purpose. The thermometer is then replaced in the horizontal position.

38. Negretti and Zambra's maximum.—This instrument differs from the above in having no separate index, so that the column marks its own maximum. The tube is bent, more or less, just above the bulb; and a slight constriction at the bend causes the mercury column to break at this point, when the fluid begins to contract. The column, therefore, remains at the highest point.

This thermometer is set by merely detaching the suspension ring at the bulb end, and lowering that end of the instrument towards the vertical, or, if more be necessary, by removing it and gently jerking the lower end of the mounting on the palm of the hand.

39. Phillip's maximum.—This thermometer is constructed with a small bubble of air introduced into the column at about 1½ inches from the end. When the mercury contracts after reaching its highest point, all that portion beyond the air bubble remains, marking the highest temperature reached. In the use of this thermometer, it is necessary that the direction in §42 should be strictly observed. If the stem is horizontal, the elasticity of the air bubble will sometimes drive forward the column above it half a degree or more, and derange the reading by that amount.

This instrument also is set by detaching the suspension at the bulb end, and gently lowering the instrument towards the vertical.

40. Minimum thermometer in air.—The object of this thermometer is to register the lowest temperature to which the air has cooled during the night. It will suffice to describe that form of the instrument in which the fluid is spirit, and which is in universal use in India.

41. Rutherford's minimum.—This is a spirit thermometer, with a horizontal column, and has a small black glass rod (of the form of a pin with a head at each end) immersed in the column. The spirit adheres to this, so that, if even the thermometer be inverted, it will not leave the spirit. Consequently, when the fluid contracts, the glass pin is drawn back to the lowest point reached; but when the spirit expands with an increase of temperature, the index remains at its lowest position, and the spirit passes freely by it. The *upper end of the index* (that furthest from the bulb) indicates the minimum temperature. Before the reading of a spirit thermometer is recorded, the upper part of the tube, *and particularly that part covered by the brass staple* which fixes it to the scale, should *invariably* be examined, to ensure that the column is entire and that no drop of spirit has become detached and lodged in the upper part of the tube. If such is the case, the reading must be rejected as untrustworthy, since it is uncertain whether the separation took place before or after the index reached its position.

To re-set the thermometer after an observation, hold it in a vertical position, bulb upwards, and the index will fall slowly till it reaches the upper end of the column.

42. Suspension—The above thermometers are to be suspended with the column nearly horizontal, (the bulb end about half an inch lower than the upper end of the scale).

43. Restoration of a broken column.—Spirit thermometers are very liable to derangement in travelling, by the separation of the spirit column; which, instead of being continuous, becomes distributed in two or three divisions through the upper part of the bore. Sometimes the index is shaken out of the spirit and is found fixed at the upper end of the bore. And, when the instrument is in use and not subject to concussion, it frequently happens that the vapour which fills the upper part of the tube is condensed in a drop in its upper part (not seldom beneath the brass staple that fixes the tube). In order to rectify the column, proceed in the following manner:—

(1.) If the thermometer be provided with a stout attached scale of wood, porcelain, &c., grasp it in the right hand by the upper end, holding the bulb end downwards (and taking care not to press on the tube, which might risk breaking it). Stretch out the arm above the head, keeping the bulb at a distance, and swing the instrument down rapidly towards the feet. This movement, repeated a few times, will generally restore the column.

(2.) In the case of a grass radiation thermometer [§ 50] which has no attached scale, the above proceeding is dangerous, as the thermometer is likely to be flung out of the protecting tube and broken. The following plan is better. Grasp the instrument between the bulb and the protecting tube with the tips of the thumb and the fore and middle fingers of the right hand, and grip the tube in the fork of the two fingers. Then, holding the left hand, palm upwards, hit it smartly with the base of the right hand, repeating the blow until the index is dislodged, and the column restored. The mode of holding the thermometer is shown in the accompanying figure [Figure 8].

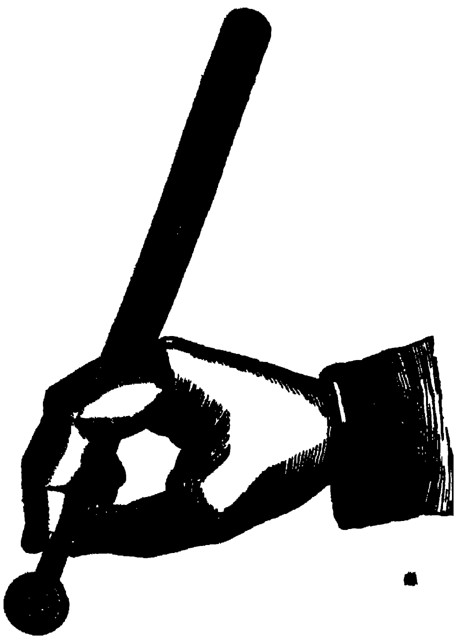


Figure 8. Method of holding thermometer to restore column.

44. **Sykes' thermometer.**—This instrument registers both the maximum and minimum temperatures in a single tube. The tube is bent in the shape of an U, with the limbs vertical, and each limb bears a scale. One of the limbs, (we will assume the right,) terminates above in a bulb filled with spirit, while the bend of the tube and both limbs up to a certain height are filled with mercury. A little spirit is introduced into the other (or left-hand) limb above the mercury, but the bulb in which this limb terminates contains only vapour. Immersed in the spirit column in each limb is a small index, a steel pin with a light spring attached, which prevents its moving in the tube by mere gravitation. By means of a small magnet, it may, however, be moved up and down; and, in setting the instrument, both indices are made to rest on the top of the two mercurial columns. When the temperature rises, the spirit filling the right-hand bulb expands and pushes the mercury column before it, causing it to rise in the opposite limb. The minimum index remains in its original position, but the maximum index in the left-hand limb is pushed before the advancing mercurial column, and on the retreat of the latter is left, marking the highest temperature reached. With a falling temperature, the spirit contracts in the right-hand limb,

followed by the mercurial column, which then drives the minimum index before it and leaves it marking the lowest temperature.

45. Radiation thermometers.—These thermometers, being intended to register the gain or loss of heat by radiation, must be freely exposed to the sky without cover of any kind. They are of two kinds, *viz.*, a self-registering maximum thermometer for obtaining the temperature acquired when exposed, under constant conditions, to the sun's radiation; and a self-registering minimum for ascertaining the loss of heat by radiation to the sky during the night.

46. Solar radiation thermometer.—The use of this instrument is to give a relative measure of the intensity of the sun's heat. It consists of a mercurial maximum thermometer, (the bulb of which, together with a portion of the stem, is coated with lamp-black,) enclosed in a larger tube, from which the air has been exhausted before being sealed.

The lamp-black absorbs the radiation from the sun, as well as that which it receives from all objects around, and thus the bulb of the thermometer becomes heated. At the same time it is giving out its own heat to surrounding objects; and the temperature shown by the thermometer becomes constant, when the heat given out in each second of time is exactly equal to that which it receives. Any change made in the surroundings, for instance, the substitution of grass for bare earth beneath the instrument, of a white-washed wall for a naked brick-wall in the neighbourhood, or a wall for a bush, alters the conditions of equilibrium. Consequently, in order that the readings at one time may be strictly comparable with those at another time—in other words, in order that the instrument may show the variations of the sun's radiation and no other,—the surrounding conditions must always be the same. This means that the thermometer must always be exposed in the same place, with the same objects around, and at the same height above the ground. At Allahabad there was a difference of 6° between the readings of two thermometers otherwise reading alike, when one was placed over thickly-growing grass, the other where the grass was somewhat thin, on one and the same lawn.

The outside of the enclosing tube being exposed to the air, the temperature of the tube is lowered by its contact, and, as this tube surrounds the thermometer, the temperature of the latter is affected in its turn. When the sun is shining, the air close to the ground is hotter than that at a greater height above it. Hence, a further reason that the thermometer must always be at the same height above the ground. The effect of the sun's radiation is indicated by the *difference* of the temperature shown by the solar thermometer and that of the air.[a]

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[a] In practice this is the difference between the maximum of the radiation thermometer and the maximum shade temperature.

Owing to circumstances not yet fully explained, there is frequently a great difference in the readings of solar thermometers of the same pattern, amounting to two or three degrees, and sometimes very much more. It cannot, therefore, be assumed that the readings of two thermometers are even approximately comparable with each other, unless they have previously been compared by exposure to the sun, side by side, under precisely the same circumstances.

The vacuum in these thermometers is frequently far from perfect, and is variable. The more air there is in the tube, the more does it cool the thermometer by convection. If, therefore, the outer tube be cracked, however slightly, air penetrates and the thermometer must be rejected as unserviceable.

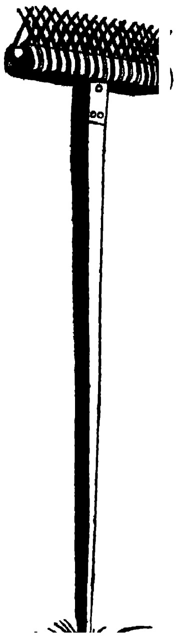

Figure 9. Sun thermometer stand.

47. Stand for sun-thermometer.—Until lately it was the practice at most stations in Bengal to expose the sun thermometer on two forked sticks, one foot above the ground. In this position, however, its indications are so greatly influenced by the condition of the small patch of ground immediately beneath the instrument, that it has been found better to expose it on a stand four feet high, which somewhat diminishes the merely local effect. This plan has been recommended as the result of some experiments made by Mr. Stow in England. The stand adopted by the Meteorological Department is represented in Figure 9. It differs from that recommended by Mr. Stow chiefly in being provided with a cage of sharpened wires, which are very necessary in India to prevent crows and other mischievously disposed birds resorting to the stand as a perch.

This stand is introduced only at newly-established stations, and at others where, owing either to the destruction of the thermometer, the removal of the observatory or other cause, the strict uniformity of the observations has been interrupted. Otherwise, it is of more importance to obtain observations strictly comparable with those of former years than to introduce an improvement in the exposure.

48. Time of exposure.—**On a clear day, the sun's greatest heat is at noon, and the highest temperature recorded by the sun thermometer occurs shortly afterwards; since, for a short time, the increase in the temperature of the air and of radiating objects around, more than counteracts the decrease of direct solar radiation. But the sun thermometer should be exposed at least from 10 A. M., to 4 P. M., since, if**

clouds are about, the highest radiation temperature may be either earlier or later than noon. It should always be removed during the night, *and carefully wiped clean* before it is replaced on the stand next day.

In the earlier months of the year (February to April) in which hail sometimes falls, the thermometer should be read and removed when a storm is imminent.

49. Comparison of sun thermometers.—These thermometers cannot be sufficiently compared in the ordinary way, since their irregularities are affected by variations in the vacuum of the tube, the extent of the lamp-black coating, and probably other causes not inherent to the graduation; a rigorous verification of the thermometer in respect of contact temperatures would, therefore, be of little use. The method now adopted is to select one instrument as an arbitrary standard, and to reduce the readings of all others to the same value, after comparing them by free exposure to the sun, side by side, under identical conditions, till thirty or forty readings have been recorded. Comparison in the shade is no criterion of their difference in the sun. Two thermometers which agree well in the shade may differ by 3° or 4° in the sun.

50. Grass radiation thermometer.—At night the earth and all objects on its surface give out by radiation towards the sky the heat they have received during the day; and if the sky be clear and free from clouds, receive but little in return. Being at first warmer than the air, they continue to cool down below the temperature of the air, and eventually cool the air itself in contact with them. If any screen, natural or artificial, be interposed between any object (thus cooling) and the sky, the radiation is arrested, and in part reflected. A cloud, a tree or an umbrella thus checks radiation at once.

The object of the grass radiation thermometer is to ascertain the extent to which such cooling proceeds, and it follows from what has been said that it must be freely exposed, away from trees or buildings. It has been usual to place it on grass or other closely-growing vegetation, but above it and quite unscreened by it. It consists of a minimum thermometer without any attached scale, the tube being graduated. To give the instrument greater strength, the stem is generally enclosed in a stout glass tube [Fig. 8]. It is set in the same way as an ordinary minimum; and must be placed horizontally on the grass or, failing this, on a surface of wool, such as a piece of country blanket [§ 51].

The enclosing tube is rarely air-tight, and damp air sometimes enters and deposits dew on the inside, which, if allowed to accumulate, much obscures the readings. In such case the thermometer should be taken out, the tube wiped out dry, and the thermometer replaced. This should be repeated as often as necessary. If the graduation becomes obliterated, it may be easily rendered distinct by the proceeding described in § 52.

51. Exposure and protection.—In countries, such as some parts of the Punjáb, Rájpútána, and the Dekhan, where, during the hot weather, grass will not grow, and where the ground is bare or nearly so, perhaps for miles around, no attempt should be made to produce an artificial grass surface by watering. The evaporation from the watered surface will affect the temperature quite as much probably as radiation. In such cases it should be laid on a piece of dark coloured country blanket of three or four-fold thickness, nailed on a board, and laid on the ground.

Radiation thermometers are more liable to destruction by birds and animals than other kinds of thermometers, but *no screen of any kind must under any circumstances be placed over their bulbs.* With a little care and attention they may be preserved for a long time uninjured. The place where they are exposed should be surrounded by a strong fence, and, if birds are very troublesome, a stick, with a few strips of rag attached, or a light whirligig a short distance from the instrument, will generally suffice to scare them.

The grass radiation thermometer should be removed during the day to a secure place.

52. Restoration of obliterated graduation on tube.—The black pigment with which the graduation on thermometer tubes is rendered distinct, is sometimes washed out, and the graduation becomes difficult to read. It may be restored by rubbing a little common lampblack powder along the tube with the finger, the powder being used either dry, or better, slightly moistened. A trial or two will show the pressure to be used in rubbing the powder into the engraved marks and afterwards wiping off the excess; which may be done by pressing lightly, without removing that in the incisions on the stem.

ACTINOMETER.

53. Object and principle.—A sun thermometer shows the temperature attained by exposure to the rays of the sun, under certain definite conditions, but it does not show the *quantity of heat* received from the sun. For this purpose we must resort to the actinometer.

The actinometer is an instrument for measuring the quantity of radiation received from the sun in a certain fixed time, say a minute. It consists essentially of a thermometer having a very large bulb, so constructed that it will absorb the whole, or nearly the whole, of the sun's radiation. When exposed to the full sunshine, it absorbs the radiation, but at the same time it is radiating away its own absorbed heat; and this the faster, the higher its temperature. The whole quantity, therefore, received from the sun in the minute, is that which is measured by the expansion of the fluid, *plus* that which it radiates away in the same time. This latter quantity is ascertained by observing the expansion of the fluid in the sun and its contraction in the shade, alternately, in successive minutes. The contraction in the shade is the measure of the heat lost in the minute, the expansion in the sun is the measure of that which is absorbed *in excess* of that which is lost. The sum of the two is the whole quantity absorbed in the minute. The quantity of heat thus measured is that which falls in a minute, on a surface equal to that of the solar shadow cast by the actinometer bulb on a flat surface at right angles to the path of the incident ray. This heat is absorbed by a constant quantity of fluid. If then we know the quantity (*i. e.*, the mass) of the fluid, its specific heat, and its rise of temperature, the product of these, divided by the surface and the time, will give the number of units of heat[a], falling in the unit of time on an unit of surface.

54. Actinometers.—A description of Herschel's actinometer will be found in the Admiralty Manual of Scientific Enquiry (Art. Meteorology), that of Pouillet's Pyrheliometer in Taylor's Scientific Memoirs, volume IV, page 45, and also in Tyndall's Heat a Mode of Motion, and Balfour Stewart's Treatise on Heat, &c. As the instrument best adapted to Indian requirements, being cheap, simple and portable, and little liable to derangement, Hodgkinson's actinometer is that which I shall select for description here, merely premising that the principle is the same in all.

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[a] The unit of heat in English measures is the quantity of heat that will raise 1lb avoirdupois of water from 0° to 1° Fahrenheit. For the further explanation of this and other terms here employed, see Part II.

55. Hodgkinson's actinometer.—A full description of this instrument and the method of using it will be found in the Proceedings of the Royal Society, volume XV, page 321, and also in the Philosophical Magazine, 1867, volume XXXIII, page 304. In form it bears much resemblance to a thermometer, with a spherical bulb about one inch in diameter. The stem has a very fine bore up to within two inches of the top of the scale, where it expands into a wide tube 1½ inch long, and terminates above in an ellipsoidal bulb, somewhat wider than the tube. It is attached to an ivory scale, the lower end of which is 1½ inch above the spherical bulb. The scale of the narrow bore is graduated in millimetres, and it is the expansion and contraction in this portion of the stem that is the subject of observation. The scale of the wide tube at top is graduated as a thermometer, having a centigrade division on one side, a Fahrenheit division on the other. In two instruments before me, the zero of the millimetre graduation corresponds to 40° Fahr. of the thermometer scale; and in one 255mm., in the other 269mm. correspond to a range of 5°. The fluid is alcohol, coloured deep blue (opaque, except in a thin film,) with aniline blue or litmus.

When in use, the spherical bulb is inserted through a lateral opening, and adjusted in the axis of a brass tube 2½ inches wide and 22 inches long, blackened inside, and having at each end a glass cover and an outer brass cap; both of which are removable at pleasure. The stem of the actinometer above the bulb is clasped by a split cork, which closes the lateral opening in the brass tube. This tube is movable about a horizontal axis fitted with a brass pin; which, together, allow of a free movement in altitude and azimuth. The pin works in a socket, which, when the instrument is in use, may be screwed into the top of a staff of convenient height, which, being driven into the ground, serves as a support.

56. Use of the actinometer.—Thus arranged, the tube is pointed to the sun; and, the brass caps being removed, it is adjusted in this position, by the foreshortening of the shadow, or by the shadow of the bulb and tube thrown on any light-coloured surface at the lower end of the tube. The instrument may be used either with or without the glass cap. But, as this cap stops a considerable portion of the sun's heat, the difference of the readings with and without the cap must be ascertained by repeated comparison under both conditions, with a second instrument exposed at the same time without its glass. Comparing the two sets of results, a factor is obtained, which, multiplied into the "glass-on" observations, gives their equivalent value in "glass-off" observations. A factor must thus be found for each individual glass used, and each glass must be marked to facilitate identification.

The first step is to expose the actinometer until it has acquired a convenient working temperature. What this is, can be ascertained only

by experience. It is determined by the condition that the expansion of the column during the minute of exposure to the sun should be about equal to its fall during the minute of shaded exposure. But Mr. Henessey's experience in India[a] is to the effect that it is impossible to continue a series of observations for any lengthened period (as, say, two hours) without introducing breaks of several minutes in its continuity, since "this adjustment becomes changed by any considerable alteration in the radiation."

Supposing that a proper working temperature has been found, this temperature is noted, and then all the fluid in the wide part of the column is thrown off into the upper ellipsoidal bulb. In the intruments before me, the top of the narrow column corresponds in one case to the scale temperature of 45·6° in the other to that of 45·4°. If then t be the temperature read before throwing off the upper part of the column, t − 45·6° in the one case and t − 45·4° in the other, must be added to the apparent temperature of the subsequent readings, to give the real temperature. It is required to know this, because the ratio of expansion of the fluid (alcohol) is different at different temperatures.

There should be two observers, one to give the time from a chronometer, or watch showing seconds, and to record the readings; the other to read and work the actinometer. To begin with, having brought the instrument to a convenient working temperature and thrown off, and having allowed the residual column to contract through about one-half of the scale, turn the tube to an unclouded part of the sky, and at the even quarter minute, uncap it, taking the reading at the same instant. This must be done quickly, as the column is in motion, and its position must be read by estimation to the tenth of a millimetre. After a minute's exposure, the observer with the chronometer calls "time." At the same instant the actinometer column is read off. The tube is then turned to the sun. Being duly adjusted by means of its shadow, the observer waits till a quarter of a minute has elapsed, "time" is then called, the instrument read off quickly, and the sun exposure continues for one minute, when "time" is again called, the actinometer again read off and turned away for the shade observation. A complete observation consists of two shade observations and the intervening 'sun.' But in practice it is found better to combine these, in groups of 3, 4 or 5 'sun' observations, and of the initial final and intervening 'shade' observations, and to take the mean of each. As already explained, the mean fall in the shade added to the mean rise in the sun, is the measure of the mean quantity of heat absorbed.

57. Reduction.—But in what terms? It is, of course, desirable, that the observations should be reduced to units of heat per unit of time (the

[a] Proceedings of the Royal Society, volume XIX, p. 225.

second), per unit of surface (the square foot). This, however, is not at present practicable, since prolonged and elaborate experiments are required to obtain the constants of such a reduction. For the present we must content ourselves with a reduction to the indications of a standard instrument, (that at Kew observatory) merely correcting the observations for "glass-on" temperature, and index difference. The method of obtaining the first has been already noticed: the reduction for temperature has been usually made by Kopp's table of the expansion of alcohol at different temperatures, given in Gmelin's Chemistry. This temperature correction is applied first of all, and afterwards that for "glass-on," lastly the index correction is to be applied; to obtain which, the instrument used must have been compared either directly or indirectly with the Kew standard.

The altitude of the sun may be observed at the time of the observation, or may be afterwards found by calculation, the time and latitude being known.

HYGROMETER.

58. Object of the observations.—Every one is familiar with the fact that, in some states of the atmosphere, a piece of wet cloth, hung up in a shady place, will dry quickly; and that sometimes, as in the Upper Provinces in April and May, the air is so dry that the covers of books and nibs of quill pens curl up, furniture cracks and opens at the joints, &c., owing to the evaporation of the small quantity of moisture that these articles usually hold absorbed. On the other hand, during the rains in Eastern Bengal, on the west coasts of India and Burma, &c., it is almost impossible to keep books, clothes, &c., from becoming damp and mouldy. These differences depend on what is termed the humidity of the air, that is to say, on the quantity of vapour it contains. In the former condition the air is said to be dry, in the latter very moist. The object of the hygrometer is to ascertain the quantity of vapour actually present in it.

59. Absolute and relative humidity, saturation and dew point.—The quantity of vapour which can exist in a given space depends on the temperature, and is appreciably the same whether air is present or absent. It is the greater the higher the temperature, but rises in a much more rapid ratio. It is but rarely that the air contains this maximum quantity, except in cloud or fog, and it is then said to be *saturated*, whatever may be the temperature. If the air is below saturation, the quantity of vapour in it is expressed as a percentage of that required to saturate it at the actual temperature. This percentage is called its *relative humidity*, and it is upon this ratio that what we term its dryness or dampness chiefly depends; for the same quantity of vapour that would saturate the air or represent 100 per cent. of humidity at a temperature of 50°, would represent only 30 per cent. of saturation (a very dry atmosphere) at a temperature of 85°.

The *absolute* quantity of vapour present in the air may be expressed either by the number of grains in each cubic foot, or by the temperature at which it would just suffice to saturate it. This latter is termed the *dew point*, because, if a mass of air is gradually cooled down, it begins to deposit some of its vapour either as a dew or fog as soon as it reaches that temperature. Thus, in the case above given, the temperature of the air being 85° and its relative humidity 30, the dew point will be 50°. A third and still more common mode of expressing the quantity of vapour in the air is in terms of its tension or the elastic pressure that it exercises, measured in the same way as the pressure of the air, *i. e.*, barometrically. This is termed the *vapour tension*, *pressure* or *elasticity*.

It has been ascertained experimentally, by introducing a few drops of water into the Torricellian vacuum of a barometer, and measuring the depression it produces at different temperatures. The latest and most trustworthy tables of vapour tension are those based on Regnault's determinations. Such a table, computed for use in India from Regnault's data, is given in the accompanying collection of tables [Table III].

60. Hygrometers.—The instruments chiefly used for measuring the vapour in the air are Daniell's and Regnault's hygrometers, and Mason's hygrometer, also called the psychrometer. There are others, such as De Saussure's hair hygrometer; and the drying tube, the object of which last is to extract the vapour from a measured volume of air and to weigh it; but the former is not used in India, and the latter is too tedious in use for ordinary meteorological purposes. They are both described in Ganot's and Deschanel's physical handbooks.

61. Daniell's hygrometer.—The object of this instrument is to show the temperature of the dew point by cooling down the air in contact with it till dew is deposited. It consists of two glass bulbs, (one of black glass), connected by a large tube bent twice at right angles. The limb above the black glass bulb is longer than the other, and contains a small thermometer to show the temperature of the fluid (ether) which the bulb contains. The colourless glass bulb is covered with a piece of muslin. In constructing the instrument, the ether which it contains has been brought to the boiling point to drive out the air, and the tube has then been hermetically sealed. In order to take a dew point observation, all the ether is passed into the black bulb, and the instrument is then placed on its stand. The muslin-covered bulb is next moistened with a few drops of ether, which rapidly evaporates, cooling down the bulb and condensing the ether vapour within it. This causes more vapour to be given off from the black bulb, which in its turn is cooled down; and, by repeating the process, the temperature of the latter is lowered, until a ring of dew appears on the black surface of the bulb. At the instant that this is seen, the thermometer within is rapidly read off to the nearest tenth of a degree. The instrument is then allowed to stand and to absorb heat from the atmosphere and from objects around. At the instant that the dew ring disappears, the internal thermometer is again rapidly read off, and the mean of the two readings gives approximately the dew point. To obtain it accurately, the experiment should be slowly repeated.

62. Precautions.—In observing with Daniell's, and also with Regnault's hygrometer, great care must be taken to avoid breathing on the instrument, or to allow the hand or face to approach it so nearly as to bring it within the influence of the evaporation from the skin. The air around should be still; so that observations are best made in a verandah

or room communicating freely with the outside air, but without any strong draught. The instrument is not adapted for use in very dry climates. Colonel Sykes in the Dekhan and Dr. Forbes Watson in Rájpútána both failed to obtain the dew point of the dry atmosphere there prevalent in the hot weather. For such climates, Regnault's hygrometer is required.

63. Regnault's hygrometer.—The principle of this instrument is so far identical with that of Daniell's, that it consists in artificially cooling down a polished surface in contact with the air, by the evaporation of ether, until the temperature of the dew point is reached. But the means employed are more rapid and powerful, and a lower temperature can be readily produced. The instrument is, therefore, well fitted for use in very dry climates.

In its present form, as constructed by Casella, it consists of a thin metal capsule of the form of a large thimble, having a highly polished silver surface, and closed by a cork or stopper. Through this stopper passes the stem of a thermometer, the bulb of which is immersed in the ether with which the capsule is rather more than half-filled. A small metal tube passes down inside the capsule, and opens close to the bottom. To its upper end is attached a piece of India-rubber tubing, with a mouth piece, through which air is gently blown and made to bubble up through the ether. The current of air compels the rapid evaporation of the ether; the vapour of which, with the air, passes out of the vessel through another tube, the orifice of which is immediately below the stopper. By this means, the temperature of the ether is very rapidly reduced; and since the evaporation goes on from the very bottom of the fluid, and the whole mass is stirred up by the passage of the air bubbles, the cooling is equal throughout; the capsule is cooled at the same time; and, as soon as the dew point is reached, its highly polished surface is rendered dull by the deposited dew. The thermometer is then read off rapidly. The first observation will probably give only an approximate reading, since the thermometer falls very quickly; a second and third experiment, made more slowly, will give it accurately to the tenth of a degree.

So rapid is the action of this instrument, that in some observations made by the author at Secunderabad, at a temperature of 93° and with a dew point of 51°, representing a relative humidity of 24, six observations were made in a space of six minutes, and at Bellary, at a temperature of 96·1° and a dew point of 47·8 (equal to a relative humidity of 19), five observations were made in the space of ten minutes.

64. Mason's hygrometer or August's psychrometer.—The instruments above described have the advantage of determining the quantity of vapour in the air by direct methods. But they are not adapted for general use; being expensive, and requiring also some little skill in mani-

pulation. Mason's hygrometer gives an indirect indication only, but its use is simple, and, being self-acting, an observation consists simply in reading off a pair of thermometers.

It consists of two thermometers, one of which shows the temperature of the air, the other the temperature of an evaporating surface. This latter has a piece of muslin tied closely over the bulb and kept constantly wet by a bundle of cotton threads, which dip into a small vessel of water. The water is sucked up by the thread in the same way as oil is sucked up by a lamp-wick, and, spreading through the muslin, evaporates from the surface of the latter, with greater or less rapidity, according as the air is relatively dry or moist.

65. Principle of wet bulb.—Most persons are acquainted with the action of a wetted tatty in cooling the air that passes through it, and also with the common mode of cooling water by hanging a vessel of it surrounded by a wet cloth or damp straw in a shady place, exposed to a hot dry wind; or, what amounts to the same thing, in a vessel of porous earthenware, the outside of which is kept constantly wet by the water soaking through from within. In all these cases, coolness is produced by the evaporation of the water; and the faster the water evaporates, the greater is the cold produced. Thus it is with the wet bulb of the hygrometer; it is cooled by evaporation, and the temperature falls the lower, the more rapid the evaporation. The dry bulb thermometer shews the actual temperature of the air; and the difference of the readings of the dry and the wet bulb increases with the rate of evaporation, and this again increases with the dryness of the air. It does not, however, increase in the *same* ratio at different temperatures, nor is the wet bulb ever cooled down to the temperature of the dew point.

In computing the dew point from the depression of the wet bulb, it is assumed that the air around the bulb gives up heat sufficient to evaporate the additional quantity of water requisite to saturate it; and that, this atmosphere being constantly renewed, the wet bulb is kept at the temperature to which it is thus depressed.

66. Precautions.—It follows from the above that the air around the wet bulb must not stagnate. A gentle current should at all times pass across the bulb; and this conclusion from theory is borne out by observation. In a still atmosphere, as, *e. g.*, in a room, the wet bulb gives a reading higher than that supposed by the theory, and the humidity calculated from such an observation is too high. In the thermometer shed, the conditions are, in general, those required for good observation; but, if the air is quite calm, the wet bulb should be fanned by a hand punkha before the reading is taken. Under any circumstances, the sling thermometer, used as described in §33, gives a good result.

Distilled water or clean rain-water only should be used for moistening the bulb. River, tank, and spring-water contain salts which, on the evaporation of the water, are left encrusting the bulb and forming a stony deposit, which destroys its sensitiveness. In most parts of India, a supply of rain-water is easily procured and stored for use. In Sind and the drier parts of Rájpútána and the Punjáb, where no other than river or well-water is procurable, a supply of water should be well boiled and then allowed to stand before being used; and the bulb of the thermometer must be frequently examined and cleaned by the use of acid and careful scraping with a *sharp* pen-knife ; but this requires great care. Observations made with an encrusted bulb are only misleading.

A small bottle with a narrow neck (to prevent useless evaporation) is the best form of reservoir. Keep it always full or nearly so.

Place the bottle with the neck a little on one side of the thermometer and about half an inch *below* it. [See Plate I.]

The bulb must always be well wetted. The muslin and thread must be washed at least once a week, and removed and renewed once or twice a month. Care must be taken that neither the muslin nor thread is greasy, but that they absorb water freely. If, in dry weather, the wet and dry bulbs give the same or nearly the same reading, the former is not properly wetted.

The muslin must be thin and fit closely to the bulb, and the wick that supplies it with water must be sufficiently thick to supply it freely. A strip of muslin, loosely twisted, is a good substitute for the wick.

67. When the wet bulb freezes.—At hill stations in the winter time, the wet bulb not infrequently falls below the freezing point. When this is the case, the water in the supply wick is frozen, and the bulb soon dries. It is then necessary to dip the bulb in water and to allow a film of ice to form *half an hour before* each observation is taken. After being dipped, the first film should be allowed to freeze, and a second dipping will produce a film of ice thick enough to last till the time for observing the depression.

In reading the hygrometer, the same precautions are to be observed as in the case of the thermometer. [See §28.]

68. Computation of vapour tension and the dew point.—Two formulæ, both based on the assumption specified in §65, are in use for this purpose.

69. Apjohn's formula.—That most frequently used in England was originally proposed by Dr. Apjohn, after whom it is called, and is as follows :—

$$(a) \quad F = f' - \frac{t-t'}{88} \quad \text{or}$$

$$(b) \quad F = f' - \frac{t-t'}{96}$$

when F is to the vapour tension at the dew point; f' that of saturated vapour at temperature t'; t the observed temperature of the dry, and t' that of the wet bulb thermometer; and h the height of the barometer (reduced for temperature) at the time of reading. The formula (*a*) is to be used if t' is above 32°, and formula (*b*) if below it. The value of f' is found in a table of vapour tensions, of which Regnault's and those based on his determinations are the most accurate [Table III]. When F has been computed, the same table is referred to, and the temperature at which F is the tension of saturated vapour is that of the dew point.

70. August's formula.—The other formula is that proposed by August, the constant values of which have been since corrected by the results of Regnault's determinations*. In its abridged and simplified form, omitting certain terms which affect the result but slightly, and adapted to Fahrenheit temperatures, it is as follows:—

$$F=f-\frac{0\cdot480\ (t-t')}{1180-t'}\ h$$

for all *wet-bulb* temperatures above the freezing point, and for those below it—

$$F=f-\frac{0\cdot480\ (t-t')}{1240\cdot2-t'}\ h$$

Tables calculated by this formula for the barometric pressure $h=29\cdot7$ inches will be found in Guyot's *Meteorological and Physical Tables* published by the Smithsonian Institute at Washington; and Tables adapted to the mean latitude of 22° and the mean barometric pressures 29·7, 27·7, 25·8, and 23·4 are given in the collection of Tables which accompany this hand-book [Tables IV, VI, VIII and X]. These may be used for stations at all elevations up to 8,000 feet without serious error.

71. Glaisher's factors.—Mr. J. Glaisher has endeavoured to save observers some of the trouble of computation, by determining empirically certain factors, which, multiplied into the difference of the wet and dry bulb thermometers, will give the difference between the temperature of the air and that of the dew point. The result is approximately correct for high and moderate humidities, and for stations at and near the level of the sea; but the factors cannot be used for elevated stations, since they take no account of variations of pressure.

72. Comparison of different methods.—The results afforded by the above three methods agree only approximately, and it has long been a desideratum to compare them severally with the vapour tension of the dew point given by direct observation with Daniell's or Regnault's hygrometer. Some observations made with that view by the author

* For the rational development of this formula the reader may refer to the translation of Regnault's paper in Taylor's Scientific Memoirs, Vol. III, or to the original in the *Comptes Rendus* for April 1845.

at Secunderabad, Bellary, Coimbatoor, and Trichinopoly in April 1875 seem to shew that August's formula, as given above, is the most trustworthy. The observations were made in the thermometer sheds at the stations mentioned, where therefore the wind could act on the psychrometer. The temperatures varied from 92° to 97° in the shade, the dew points from 46·5 to 54·2, and the relative humidities from 18 to 26. The mean of 10 sets of observations computed by Apjohn's formula gave a mean error of +4·8°, Glaisher's factors one of +3·4°, and August's formula one of +1·0° only. The three methods require further testing, but meanwhile August's formula appears to give the best results.

73. Computation of relative humidity.—The vapour tension at the dew point having been ascertained as above, the relative humidity is computed by the formula $H = \frac{F \times 100}{F}$; wherein, F is the vapour tension at the dew point, and F that of saturation at the temperature shewn by the dry bulb thermometer.

When a table of vapour tensions has been computed for any station for the required range of readings of the dry and wet bulbs, a table of humidities is easily calculated therefrom for the same mean pressure. [See Tables V, VII, IX and XI.]

74. Self-registering psychrometers.—Self-registering maximum and minimum thermometers may be fitted up as wet bulbs to record the highest and lowest temperature of evaporation during the day. The latter is an important adjunct to the record, as the lowest evaporation temperature, as a rule, coincides nearly with the lowest reading of the dry bulb and also with the time of *maximum* humidity of the day. The maximum wet bulb is, however, of little use, as, in the dry climate of Upper India, the highest temperature of evaporation frequently falls some time in the morning or evening, and rarely at the same time as the maximum of air temperature.

75. Corrections of instruments.—The corrections of the thermometers employed as hygrometers are to be applied to their readings before the latter are used to compute the humidity, &c. Both thermometers are to be read to the nearest tenth of a degree; and in using tables of vapour tension and humidity, values for fractions of a degree are to be obtained by interpolation, as described in the directions prefixed to the Tables.

RAIN-GAUGE.

76. Object and principle.—The object of the rain-gauge is to show the quantity of rain that falls. This is expressed in inches and decimal parts of an inch; the meaning being that, if the rain were to fall on a level surface which does not absorb it, and from which it cannot run off or evaporate, it would form a sheet of water so many inches or parts of an inch in depth.

77. Construction.—The instrument consists essentially of a funnel with a square or round mouth, and a receiving vessel. The quantity of rain received is determined by *the area of the mouth of the funnel;* and this area, if the rim of the funnel is round, is equal to the square of half its diameter multiplied by 3·1416. Thus a circular funnel, 4 inches in diameter, has a receiving area $(\frac{4}{2})^2 \times 3{\cdot}1416 = 12{\cdot}5664$ square inches. One six inches in diameter $(\frac{6}{2})^2 \times 3{\cdot}1416 = 28{\cdot}2744$ square inches, &c. Any change in the form of the opening, (such as may be produced by a blow or a squeeze,) diminishes its area, and the gauge will no longer register truly, and must be rejected. To provide against any accident of this kind, the rim of the funnel is generally strengthened by a stout brass ring.

The reservoir is either a large bottle, or a vessel of sheet zinc or copper, or tin plate; but this last is objectionable, being liable to rust. The water received is measured either in a graduated glass measure, or by means of a dip stick; or a light graduated rod, carried by a float which rises as the water accumulates. Some gauges are provided with certain mechanical arrangements for recording the rainfall on a dial, but these need not be described here.

Those with a graduated glass measure are all alike in the essentials of their construction, differing only in shape, dimensions and certain other details; and bear the different names of their inventors, as Symons' gauge, Glaisher's gauge, &c. The float gauge is generally known as Fleming's gauge. It will be necessary to notice those only that are in common use in India.

78. Symons' gauge.—This is the most convenient and trustworthy form of gauge, and is now used exclusively throughout Bengal and in some other provinces. It is a small cylindrical gauge, five inches in diameter and fourteen inches high. The water is received in a large glass bottle, and it is measured in a cylindrical glass, holding a quantity which represents an inch (or half-inch) of rainfall when filled up to a certain fixed mark. The space below is graduated in tenths and hundredths of an inch.

The gauge, as made in England, is intended to stand on the ground, or to have the bottom buried to the depth of two or three inches. In Bengal it is furnished with a foot of the form shewn in the figure, (Figure 10,) which gives it a firm hold in the ground and preserves it from the danger of being blown over. It is to be buried to the line A B.

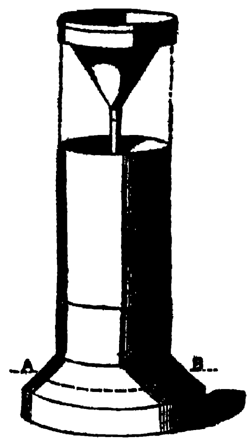

Figure 10. Symons' rain-gauge.

To measure the rain, lift the inner receiver and pour the rain cautiously, (so as to spill none) into the measuring glass, placed on a large empty dish. The glass will hold one inch. If more than one inch have fallen, the glass must be filled exactly to the one-inch mark, then emptied and re-filled, until all the rain collected has been measured. The pouring requires some care, and should be done over a large dish to catch any that may accidentally be spilled. The receiver (if of metal) should have a small lip or spout to facilitate pouring. The measure glass belonging to a rain-gauge is graduated for a receiving surface of definite dimensions, and cannot be used for a gauge of different diameter without a special calculation. A glass graduated for use with a 5-inch gauge may be used for any gauge of that diameter, but not for a 4-inch nor an 8-inch gauge. On an emergency, rainfall may, of course, be measured in any graduated glass, the exact capacity of which is known; but every reading in a register so kept must be reduced by calculation, the data for which are,—the diameter of the gauge funnel, its form whether round or square, and the value of the graduation either in cubic inches or fluid ounces. The latter may be converted into cubic inches by multiplying by 1·733, and this product divided by 3·1416 times the square of half the diameter of the funnel in inches, if the funnel be round, will give the depth of the rainfall. This rule may be useful at stations where a broken measure glass is not easily replaced without delay, since an ordinary apothecary's fluid measure glass can generally be procured for temporary use.

79. **Glaisher's gauge.**—This is similar to Symons' gauge, but is larger, *viz.*, 8-inches diameter. It appears from the comparative experiments made at Calne by a committee of the British Association, that this presents no advantage in point of accuracy over the smaller gauge. The spout at the base of the collecting funnel is bent, whereas that of Symon's gauge is straight; but this is rather a disadvantage, as it is more liable to become choked by the accumulation of dust, &c.

80. **Fleming's gauge.**—The receiver of this gauge is long and narrow, and contains a float (nearly as broad as the receiver,) carrying a light brass or wooden rod, which rises as the rain accumulates; passing through

a perforated bar across the mouth of the funnel. This bar serves as an index, and shows, by its intersection with the rod, the quantity of rainwater in the receiver. The float requires a certain quantity of water (variable in different gauges) to float it and bring it to the zero mark; and this quantity ought always to be kept in the gauge, a matter requiring some attention during dry weather. Failing this, the quantity required for flotation must be ascertained and added to the quantity read off. Should the rain be too small in quantity to bring the rod to the zero point, it cannot be accurately recorded. This gauge, therefore, in the hands of unskilled and inattentive persons, (and they are many,) is likely to give results always in defect of the truth, and such is found to be the case in practice.

The gauge is open to many other objections. If the float is dented or otherwise altered in form, or if any part has to be resoldered, the quantity of water required for its floatation is altered, and this is rarely if ever attended to. As this gauge, however, is still extensively used, attention is drawn to the following precautions:—

I.—Either enough water must be kept constantly in the receiver to retain the gauge at zero, (a troublesome matter in hot weather), or the gauge must be kept quite empty, and so much added to each reading as is required merely to bring the gauge rod to zero.[a]

II.—The gauge, being long, is liable to be blown over. It must therefore be placed in a wooden stand which is firmly bedded in the ground; or a metal cylinder or long wooden box of such size as to hold the receiver must be buried in the ground, and the receiver placed therein. In this case, the mouth of the funnel should be not less than one foot above the surface of the ground, to prevent dirt being blown or washed into it.

III.—In very heavy rains, as the cylinder will hold no more than six inches, the rain should be measured and the gauge emptied every three hours (or less), according to the quantity of the fall.

IV.—The gauge must be emptied after each observation, with due regard to the provision specified in I.

V.—The funnel which carries the index bar must be truly adjusted, and pressed home on the top of the receiver. This should be attended to before the reading is taken.

[a] This can be found by a simple experiment. Pour water into the empty receiver till the gauge is brought to zero. Pour it out again into an empty glass. Then, having poured a second portion of water into the receiver, and again brought the gauge to zero, return the first quantity into the receiver, and the gauge will shew the quantity it contained.

VI.—Sometimes the float does not rise freely, but either sticks in the receiver or is detained by the friction of the rod against the index bar. Before taking the reading the float rod should be lifted with the finger and thumb and then allowed to fall freely and adjust itself to the point of free flotation.

81. Site for rain-gauge.—This is a matter requiring some judgment. First the gauge should always be *on the ground,* and not on a building of any kind; unless more than one gauge are registered, and it is especially required to know the quantity collected at a certain elevation. This is always less than on the ground, and the variation is especially rapid within a few feet of the ground. In the experiments made at Calne, under the superintendence of a committee of the British Association, in the years 1863 to 1867, with gauges at different elevations, it was found that a gauge with its mouth on the level of the ground gave, on the average of the 4½ years, 6·7 per cent. more than one with the mouth one foot above the ground, and a gauge at the height of 20 feet gave nearly 5·7 per cent. less than the latter. It is, therefore, necessary, in order that the results may be comparable, that the same elevation should be universally adopted. That recommended, and now generally adopted, is that the mouth of the gauge be *one foot above the ground level.* The common practice of setting the gauge on a pillar of brick-work is a violation of the rule, and should be abandoned.

2nd.—The gauge must be as far as possible from trees, buildings, and all objects that dominate it; both that it may receive its full quota of rainfall with the wind from any quarter, and also that it may not receive droppings from trees, &c., when wind accompanies the rain.

WIND-VANE AND ANEMOMETER.

82. Construction of wind-vane.—A wind-vane, which shows the direction only of the wind, scarcely needs detailed description. The ordinary form is a balanced lever; one end of which exposes a broad surface to the wind, while the other is narrow, and serves to point the direction *from* which the wind blows, and therefore that by which the wind is designated. In ordinary wind-vanes, the vane alone revolves, and the vane rod bears a fixed cross immediately below the vane, the arms of which indicate the four cardinal points. By comparing the pointer of the vane with these, its direction is estimated with ease and with sufficient exactness.

83. Compass notation.—The notation universally adopted for registering wind directions is that of the mariner's compass, or numbers from 1 to 32, corresponding to the 32 compass points. Registration in degrees of arc is resorted to only to express the mean or resultant direction of a large mass of observations.

The following are the names of sixteen compass points with their respective letter symbols and numbers. The intermediate points, north by east, north-east by north, &c., are not required in general for wind registration :—

North	N.	32
North North-East	N. N. E.	2
North-East	N. E.	4
East North-East	E. N. E.	6
East	E.	8
East South-East	E. S. E.	10
South-East	S. E.	12
South South-East	S. S. E.	14
South	S.	16
South South-West	S. S. W.	18
South-West	S. W.	20
West South-West	W. S. W.	22
West	W.	24
West North-West	W. N. W.	26
North-West	N. W.	28
North North-West	N. N. W.	30
Calm	C.	

84. Calms.—If there is insufficient wind to move the wind-vane, the position of the vane is not to be recorded; but, in lieu thereof, the

letter C, indicating a calm. The anemometer will also show whether a wind direction or a calm should be entered on the register. If the cups are motionless, or only moving slowly at intervals, with intervening pauses, a calm should be recorded.

85. Dial vanes.—The wind-vanes, supplied to some of the meteorological stations, are made with the vane firmly keyed to the vane rod, which is so suspended as to revolve with the vane; and, passing through the roof (of the house on which it is fixed) to the room below, shows the direction of the vane on a fixed dial, by a pointer keyed on the rod, and exactly parallel with the pointer of the vane above. The advantage of this form is, that it may be read at night as accurately and conveniently as by day.

86. Choice of site and fixing.—In selecting a place for the wind-vane, the following points must be attended to:—

1. The place selected must be as open as possible, and there must be no object loftier than the wind-vane for a long distance (as far as possible), around. Large trees and buildings in the neighbourhood are always objectionable. Even if not lofty enough to screen the vane, when the wind blows from their direction, they nevertheless serve to cause eddies, such as may frequently be noticed in streets, and among buildings, which act on the vane from a direction different from that of the general current.

2. The vane must be fixed on the highest accessible point. If on a building, it should be fixed on the highest point of the building and at least four feet above it. It must, however, be easily accessible for the purpose of oiling, &c.

3. Its cardinal points must be set by compass, (and not by guess,) to true, (not magnetic) north. The declination of the compass (or difference between magnetic and true north) is very small in any part of India, not exceeding 2°, and magnetic north is east of true north. This variation, small as it is, must not be disregarded; for it must be borne in mind, as an universal law, that all errors which are constant in direction, however small and however roughly approximate the observations into which they enter, are reproduced to their full and true amount when the average of a very large number of observations is taken.

87. Beaufort's scale of wind-force.—In the absence of any instrument for registering the pressure or velocity of the wind, this, after some practice, may be estimated in such a manner as to give a useful record, and expressed in the scale of numbers proposed by Admiral Beaufort. These for stations on land are as follow:—

Calm	0
Light wind	1
Moderate	2

Fresh	3
Strong	4
Heavy	5
Violent (hurricane)	6

88. Pressure gauges and anemometers.—There are two classes of instruments in common use; one intended to show the pressure of the wind on a surface of constant area; the other designed to show the rate of its movement, or rather the actual distance travelled by it.

The former class comprise such instruments as Lind's and Osler's wind-gauges; the latter such as Whewell's, Robinson's, Casella's and Beckley's anemometers. Each of these will be briefly described.

89. Lind's wind-gauge.—This consists of a glass tube bent in the form of the letter U, and partly filled with water. Both limbs are open above, and one of them is bent round at top into a horizontal position, so that the opening may face the wind. This open end is sometimes furnished with a trumpet-shaped head with a view to enlarge the area of the opening on which the wind acts. The tube is attached to a broad vane and poised on a pivot, so that the opening is constantly presented to the wind. The pressure of the wind on the air which fills the upper part of the tube, between the opening and the water, is transmitted to the water, which is therefore depressed in the proximal limb and raised in the distal limb, and the difference in the height of the two columns indicates the pressure of the wind. This is read off on the gradation, which in the proximal limb is carried below the level of normal equilibrium, in the distal limb above it. This instrument, of course, serves to show the pressure, only at the moment of observation.

90. Osler's wind-gauge.—This instrument is autographic and serves to record the pressure and direction of the wind in all their variations. It consists essentially of a square plate, behind which are springs; whose elasticity serves to measure the force of the wind. This apparatus is attached to a large vane, which keeps the pressure plate at all times facing the direction from which the wind blows. To the back of the plate is attached a chain, passing over a pulley in the hollow spindle which carries both the vane and plate, the other end being fastened to a copper wire, which passes down the spindle and communicates the motions of the plate to a pencil, which traces a line on a sheet of ruled paper. The lower end of the spindle also communicates its movements, by means of suitable gearing, to a second pencil, which marks the direction of the wind on the same sheet. The record sheet is pinned to a flat board, which is made to travel horizontally beneath the pencils by means of clock-work; and the sheet is ruled in three divisions, one for recording the pressure, a second for direction, and a third, which receives the trace of a third pencil, registers the rainfall received by a gauge

beneath the anemometer. A full description of this instrument with figures will be found in Drew's *Practical Meteorology*.

91. Robinson's anemometer.—This instrument, which is now generally used at observatories, records the movement of a revolving vane by means of a train of toothed wheels; and the total movement is read off periodically on a dial, or on the wheels themselves, which are stamped with figures indicating tenths of miles, miles, tens and hundreds of miles. There are several forms of the instrument, differing in the arrangement of the wheels and the number and divisions of the recording dials. Some of the older instruments indicate the number of revolutions of the vane, from which the distance in miles must be computed.

The revolving vane is similar in all, and this is the essential part of Dr. Robinson's invention. It consists of four arms radiating horizontally in the form of a cross, and carrying four hemispherical cups of thin sheet copper. While revolving, these present alternately their concave and convex faces to the wind, and Dr. Robinson has shown by calculation, that, in virtue of the form of the two surfaces, the pressure of the wind on the former is to that on the latter, as 3 to 2. Consequently, the vane revolves with one-third of the velocity of the wind. This, however, is practically the case only with large instruments, the arms of which are two feet and upwards in length; and, in all cases, a correction has to be applied for friction, &c., which varies with each instrument, and must be determined by experiment. Small instruments always show a movement lower than that of large instruments, and less than that indicated by the theory.

In the ordinary small instruments, the revolution of the spindle which carries the revolving vane is communicated by an endless screw to the train of recording wheels. [Figure 11.] In front of each wheel is a fixed pointer, which indicates the reading of that wheel. Each wheel is divided into tenths, and the divisions are numbered from 0 to 9. There are generally five of these: the first, (moved directly by the spindle,) merely serves to communicate motion to the rest, and is unnumbered. The second indicates tenths of miles, the third whole miles, the fourth tens of miles, &c. Thus, one division of each wheel corresponds to a whole revolution of the wheel next below it.

92. Reading.—In reading off the wheels of the ordinary instruments above described, always take the lower of the two figures on opposite sides of the pointer; observing that, as 0 succeeds 9, 9 is the lower figure in the sense of this direction. If the pointer happens to be nearly over one of the figures—since these instruments are not always constructed with great nicety—a little precaution is necessary. In such case look at the wheel for the next *lower* value, and see whether its zero has passed the pointer or not. If it has passed, then the figure below

the pointer of the first wheel is to be recorded, with the lower figure of the second. But if the zero of the second wheel has not passed its pointer, it is to be concluded that the revolution is not complete, and therefore a whole division of the next wheel above it is not complete; so that, on this wheel, not that figure which is beneath the pointer, but the next below it must be taken.

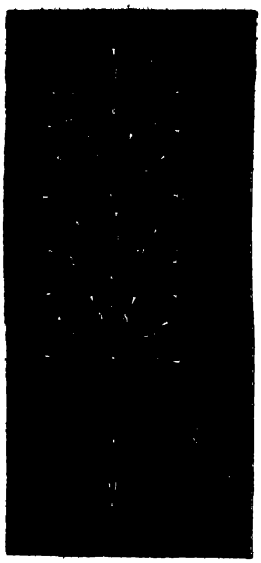

Figure 11. Train of wheels in anemometer.

In the figure appended the reading will be 073·8 miles. In the instrument from which the woodcut was engraved the highest wheel appears to be at least one tooth out of position.

These anemometers usually register up to 1,000 miles. When a reading is made, if the amount of the previous reading is deducted, the difference shows the movement of the air in the interval; and this, divided by the number of hours that have elapsed, gives the average rate per hour. When the whole train of wheel work has completed a revolution in the interval, the last reading is to be deducted from 1,000 miles, and the remainder added to the amount of the actual reading.

93. Improved dial anemometer.—In this instrument, for the train of wheels, each of which is a dial, is substituted a pair of wheels on the same axis. The front wheel of the two bears an engraved dial with two divided scales, and the readings are indicated by two pointers, one of which is fixed to the outer case of the instrument, the other is carried by the hinder wheel and revolves with it. The fixed pointer indicates the division on a circle graduated from 0 to 5 miles, the miles being divided into tenths; and a complete revolution of the dial wheel therefore indicates five miles of wind. This pointer serves to show distances under five miles. The hinder wheel has one tooth less than the dial wheel; so that, at each revolution, the pointer carried by it advances on the dial wheel through the space of one tooth. This corresponds to one division of the outer circle, and therefore to five miles. There are 101 divisions making 505 miles, (in some instruments 100 divisions equal to 500 miles,) which therefore is the maximum distance registered by this form of anemometer.

94. Reading.—This is very simple. All distances *above* five miles are read off by the position of the moveable pointer on the outer circle;

the division next behind the pointer being taken. To this is added the amount indicated by the fixed pointer on the inner circle. When, in the interval of two readings, the moveable pointer has passed the zero, the last reading is to be deducted from either 505 or 500 miles (according to the graduation of the instrument), and the remainder added to the actual reading. The reading of the dial represented in Figure 12 is $285 + 1{\cdot}5 = 286{\cdot}5$ miles.

Figure 12. Anemometer dial.

95. Beckley's anemograph.—This is an instrument on the principle of Robinson's anemometer, which records the direction and movement of the wind continuously on a sheet of metallic paper. The direction is obtained by means of a pair of wind-vanes on the principle of the windmill regulator. These are set on the same axis, and are set in motion by the wind, until they are presented to it edge-wise, when they cease to revolve. Their axis carries an endless screw, which works into a toothed disk [see Figure 13] fixed to the cast-iron standard of the instrument. The frame which carries the vanes and screw is firmly attached to a disk-shaped cover of cast iron, from which a hollow cylindrical shaft passes down inside the hollow standard, and being supported on friction rollers, the whole is made to revolve by the motion of the vanes. At its lower end, inside a cast-iron box at the base of the standard, the shaft carries a toothed disk which communicates its motion to a light hollow brass rod ; and this in its turn works the recording apparatus presently to be described.

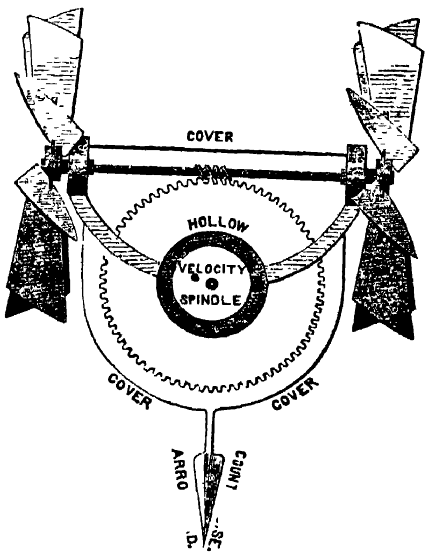

Figure 13. Direction vanes of Beckley's anemograph.

The distance travelled by the wind is obtained by means of Robinson's hemispherical cups, nine inches in diameter, carried on a frame of four arms, each two feet in length. The spindle, to which the cup-frame is keyed, passes down the axis of the hollow direction shaft, and by means of suitable gearing in the box at the base of the standard, communicates its motion to a second brass rod, which works the pencil cylinder in a room below.

The recording apparatus is placed in a room below the anemometer and consists of a clock, which turns a horizontal brass cylinder 4½ inches in diameter. This completes a revolution in (two or) three days, and carries a sheet of metallic paper, fastened by clips, and lithographed with two ruled forms, the one for direction, the other for velocity. These forms are adapted for (one or) two days' registers, and are divided transversely into hour spaces duly numbered. The direction form is ruled longitudinally with lines corresponding to the eight principal compass points. That for velocity is divided into five spaces, each of which corresponds to a movement of ten miles, so that the whole width of the form corresponds to a trace of fifty miles. Above the cylinder are two rollers, each bearing a spiral plate, the edge of which presses on the recording sheet, and, with the least friction, leaves a mark on the metallic paper. These may be termed the pencil rollers. Now, the spiral pencil makes one turn in the width of the form; and, if turned continuously, traces a line across the form, and then, coming into contact again at its further end, begins another line, which it carries across the form in like manner. But as, during this movement, the form-cylinder is being carried round by the clock work, the trace in the case of the velocity pencil becomes oblique, and the more so, the lower the velocity of the wind. The velocity pencil roller can revolve only in one direction, which is determined by that of the Robinson's cups and the intermediate gearing, while the direction pencil roller rotates one way or the other according to the veering of the wind.

The record sheet is adjusted to the cylinder by certain marks lithographed on the form. This being done, the arrowhead, which is carried by the direction disk, (Figure 13,) must be brought round by hand till it is directed to true north; (which point must have been previously ascertained by compass or a meridian observation). The 'direction' pencil roller, having been thrown out of gearing by raising the bevelled toothed wheel on the driving rod, is then set, so that the spiral pencil is in contact with the north line lithographed on the register sheet, and in this position it is brought into gearing by depressing the wheel of the driving rod, till the teeth interlock with those of the pencil roller.

On removing the record sheet, the date, the hour and minute at which it was adjusted to the roller and removed, the name of the

observatory, &c., are to be entered on the form before it is put aside.

96. Casella's anemograph.—This instrument, like Beckley's, records the movement and direction of the wind, but in a different manner. The direction is determined by the revolution of an ordinary arrow-vane, the movement of which is communicated by gearing and an endless chain to a die, which, once in every hour, (or at shorter intervals, according to the construction,) stamps the direction on a strip of paper. The edge of the paper is embossed with figures indicating the distance travelled, by means of rollers which are set in motion by Robinson's cup and ball motor.

97. Whewell's anemometer.—This consists of a vertical fixed cylinder, the surface of which is covered with varnished paper, ruled with vertical lines, corresponding to the principal compass points; and must be adjusted to the proper direction, (the marked points diametrically opposite to the true compass points,) in fixing the instrument. A vertical spindle, passing through the axis of the cylinder, carries a horizontal brass plate, which is made to revolve with the wind by means of a fixed vane attached to its upper surface. It also carries a small windmill fly which is constantly presented to the wind and rotates with a velocity proportioned to the strength of the wind. The motion of the fly is communicated by an endless screw and suitable gearing to a long vertical screw beneath the plate, causing a pencil to descend gradually and trace a line on the cylinder, the vertical measurement of which is proportional to the wind's movement. As the screw and pencil revolve with the motion of the plate, the trace is produced on that side of the cylinder opposite to the direction from which the wind blows.

When the pencil has descended through the entire length of the screw, it is unclamped and raised to the top. The trace on the varnished surface of the cylinder is measured and recorded, and then washed off.

This anemometer does not, like Beckley's and Casella's instruments, indicate the time at which the wind was blowing from any quarter; but only the direction, and distance corresponding to each direction, with the order of the changes since the last observation.

CLOUD OBSERVATIONS.

98. Object of cloud observations.—No kind of meteorological observation is of more importance than that of the forms and movements of the clouds; but it requires some study and experience to know how and what to observe, and unfortunately there is no kind of observation that, in India at least, is less satisfactory than this.

The forms and movements of the clouds afford us the only information we can obtain of the changes in progress in any part of the atmosphere above the very lowest stratum; for it is only that stratum which rests immediately on the earth's surface that we can probe and analyse, and whose motions and conditions we can study by means of the instruments already described.

In the first place, the very existence of a cloud at any elevation is an indication that the atmosphere is there in a state of saturation; and the lower the cloud, the more humid (relatively humid) is the atmosphere. In the second place, the forms of the clouds may give information as to the changes of temperature and the cause of these changes; and thirdly, their movements show what winds are blowing high up in the atmosphere, and even the rate of their movement. If indeed the height of the clouds is measured, they serve both as a wind-vane and anemometer, whose precision leaves little to desire.

Cloud observations, as usually made, include their quantity, form and movement.

99. Cloud proportion.—The proportion of the sky covered by clouds is estimated by simple inspection. A sky wholly overcast is recorded as '10' of cloud; and all minor degrees of cloudiness by the lower numbers, the figure '0' being used to indicate an unclouded sky. From the nature of the observation, an approximate estimate only is possible; but, with a little practice, it will be found easy to make it with sufficient accuracy for practical requirements. It may assist beginners, in making this estimate, to notice that, if the sky be supposed divided into five triangular segments by five equidistant lines drawn from the zenith to the horizon, each of these will be divided into two nearly equal parts by a line parallel with the horizon, and at one-third the distance between it and the zenith.

In making the estimate, clouds at a great distance, low and near the horizon, are not to be regarded.

100. Kinds of clouds.—It has been usual in meteorological treatises and registers, to adopt Luke Howard's classification of clouds, as

was indeed done in the original edition of this little manual. But, as Poëy, Fritsch, and Dr. Mann have pointed out, much confusion has arisen in the application of Howard's terminology, partly owing to defects in the original definitions, partly to the misconceptions of those who have adopted his system. In no case is this confusion more apparent than in the application of the term *stratus*. Howard's *stratus* cloud is simply fog, whether resting on the ground or at some very small height above it. But, misled by the pictorial representations given in illustration of the type, it is a common practice of observers to enter as '*stratus*' all clouds which appear as horizontal streaks near the horizon, and which being really high in the atmosphere are generally *cirro-stratus*. '*Stratus*' is an unusual cloud in India, except in the cold weather, in the damper parts of Bengal, and in the evening after sunset. Many of the objections to Howard's classification have been removed by Poëy, who, retaining certain of Howard's classes of clouds, has reclassified the others, without sacrificing the simplicity, but, on the contrary, adding to both the simplicity and definition of the system. Poëy classifies clouds as—

1. *Cirrus.*	5. *Pallio-cirrus.*
2. *Cirro-stratus.*	6. *Pallio-cumulus.*
3. *Cirro-cumulus.*	7. *Cumulus.*
4. *Pallium.*	8. *Fracto-cumulus.*

Of these, the first three and fifth are the higher clouds. The last three are the clouds of the lower atmosphere.

101. Cirrus.—This the most lofty of all clouds, appearing still at a great elevation, even when seen from the greatest heights of the Himalayas, and, as estimated by Fritsch, probably never lower than six miles. It consists of minute snow crystals forming feathery groups or brushes, parallel, diverging or curled, very thin, and always more or less fibrous in appearance.

102. Cirro-stratus.—Also a lofty cloud, but lower, denser and more sheet-like than *cirrus*. It is at such a height that it also consists of snow crystals, but is sometimes of such thickness as to dim the sun's disc, and even almost completely obscure it. When it does not extend over the whole sky it thins off towards the edges; and when seen, as sometimes in the evening and morning, low down near the horizon, it presents the appearance of horizontal streaks, which are often misinterpreted as *stratus*. Its form is very variable, sometimes it appears as a uniform sheet, at other times as broken, undulated or fenestrated layers. It exhibits the phenomena of lunar and solar halos.

103. Cirro-cumulus.—Also a lofty cloud, which forms on the breaking up of *pallio-cirrus*. One common form of it is known as a

mackerel sky, consisting of little rounded cloud tufts, more or less regularly arranged in ripple-like layers. Often appearing after rain.

104. Pallium.—Consisting of the two following.

105. Pallio-cirrus.—A thick, but lofty, sheet of cloud obscuring the sky, and forming the upper layer of the *pallium* or rain cloud. It is formed by the sinking and thickening of *cirro-stratus*.

106. Pallio-cumulus.—The thick mantle of cloud which constitutes the lower layer of *pallium* or rain cloud. Formed by the rapid increase and coalescence of *cumulus*. It extends to greater heights than ordinary *cumulus*, but is [sometimes?] separated from the higher layer of *pallio-cirrus* by a cloudless intervening stratum. After rain, it breaks up and disperses more quickly than the higher *pallio-cirrus*.

107. Cumulus.—This is one of the most familiar and typical of cloud forms, and is characteristic of the lower atmosphere. In Bengal nothing is more common, after a fine morning in the hot weather, and specially during breaks in the rains, than to witness the formation, at no great height, of isolated masses of clouds with rounded summits and flat bases, all at about the same level. These are *cumulus*; and mark the summits of ascending columns of air, which reach saturation (§ 59) at the plane marked by the bases of the cloud patches; and, above this, deposit the excess of their moisture as cloud.

108. Fracto-cumulus.—The broken, irregular, masses into which *pallio-cumulus* is resolved when in the act of breaking up, or into which it is riven by the wind. It is therefore, like *cumulus*, a cloud of the lower atmosphere, and includes the torn masses commonly termed "scud."

109. Cloud symbols.—In recording the cloud forms in the regular register, the following symbols afford a convenient abbreviated notation:—

C *Cirrus.*	Pc *Pallio-cirrus.*
Cs *Cirro-stratus.*	Pk *Pallio-cumulus.*
Ck *Cirro-cumulus.*	K *Cumulus.*
P *Pallium.*	Fk *Fracto-cumulus.*

the first letter being a capital, the second a small letter in the case of bi-literal symbols. The symbol P indicates that the sky is overcast or nearly so by a low sheet of cloud in or about the altitude of *cumulus*, and concealing all above it. When the sky is overcast by a sheet of very elevated cloud, this may be either *cirro-stratus* or *pallio-cirrus*, the latter being the lower and denser of the two.

110. Movement of clouds.—This subject deserves more attention than has hitherto been given to it in India. There is but little difficulty in observing the direction of the movement; but, like other kinds of observation, if it be attempted as a mere matter of routine, and without some

care and attention, the register is likely to be so erroneous as to be only misleading and worse than worthless.

The besetting difficulty in obtaining a true estimate of the direction of the cloud movements is the elimination of the effects of perspective. It is very difficult, and indeed impracticable without the aid of some such instrument as the nephescope of Dr. C. Braun,[a] to estimate truly the direction of clouds which are not moving either directly towards or directly away from the observer; and this, therefore, is the condition to be secured.

Set up a pointed pole, reaching 6 or 8 feet above the observer's head; and through the top, an inch or two below the point, fix two stout cross wires or thin iron rods, set truly by compass to the four cardinal points. The space around the pole must be sufficiently open to allow of a good view of the expanse of the sky in all directions. Let the observer then station himself at such a distance from the pole and in such a position that some recognizable limb of a cloud appears to move vertically upwards from the top of the pole or vertically downwards towards it. The direction of the pole from the observer's position, (which may be judged of accurately by means of the cross wires on the top,) is the direction of the cloud's true movement.

With a little care in selecting the position, the pole may be dispensed with. Any pointed object will serve the purpose, provided the observer has previously acquainted himself accurately with the directions of the compass points.

In recording the direction of the cloud movements, the kind of cloud on which the observation is made, whether *Cirrus*, *Cirro-stratus*, *Fracto-cumulus*, or other, should be noticed by its appropriate symbol. This is necessary, since the kind of cloud observed affords a rough indication of the elevation to which the observation relates.

The velocity of the movement of a cloud may be measured in favourable situations by observing the time that the shadow takes to traverse a certain space of country the distance of which is accurately known.

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[a] Described in the Journal of the Austrian Meteorological Society, 1867, vol. ii., page 337.

GENERAL WEATHER OBSERVATIONS.

Beaufort's initials and Vienna symbols.

111. In addition to the readings of the instruments, and such observations on the clouds as were explained in the last section, general observations on the appearance of the atmosphere and the occurrence of casual phenomena are a very important addition to a meteorological register. These observations should have reference not only to the regular hours at which the instruments are read, *but also to the intervening periods;* and, as far as possible, the time of each occurrence also should be noted in the register.

The principal facts to be recorded are—

1st.—The general appearance of the atmosphere and the sky during the interval preceding the observation, including the cloudiness, transparency or haziness of the atmosphere, such phenomena as coronas or halos round the sun and moon, any unusual coloration of the clouds, auroras, &c.

2nd.—The occurrence of dew, rain, hail, snow, dust-storms, thunder and lightning, squalls of wind or rain, hot winds, &c.

3rd.—The hour, or at least the approximate time, at which any of these took place.

112.* Beaufort's initials and the Vienna Conference symbols.—The former of these have long been used by English meteorological observers. They have been supplemented by certain symbols, some of which have a similar signification, while others are unrepresented in the Beaufort notation. The following are such as will be of use generally in India, while those that have application only in a cold climate are given separately. One or two symbols have been added which are not included in the Vienna Code, but will be useful in India. The use and meaning of all that do not sufficiently explain themselves will be shewn more fully below :—

Symbols.	Initials.	
	b.	Blue sky.
	c.	Partial clouds.
	d.	Drizzling rain.
≡	*f.*	Fog.
	g.	Dark, gloomy weather.

SYMBOLS.	INITIALS.	
▲	*h.*	Hail.
	l.	Lightning.
∞	*m.*	Misty, dust haze.
	o.	Overcast.
	p.	Passing, temporary showers.
	q.	Squally.
●	[illegible]	[illegible]
	t.	Thunder.
	u.	Ugly, threatening.
	v.	Visibility; referring to distant objects.
	w.	Wet, for dew.
		Thunderstorm.
		Hoar frost.
		Strong wind.
⊕		Solar corona.
○		Do. halo.
		Lunar corona.
		Do halo.
		Aurora.

The following are new :—

SYMBOLS.	INITIALS.	
		Dust whirl or 'devil.'
		Dust storm.
		Hot wind.

For cold climates, such as the hill stations in winter—

SYMBOLS.	INITIALS.	
✱	*s.*	Snow.
△		Soft hail.
V		Silver thaw.
~		Glazed frost.

113. Blue sky (*b*).—For a *cloudless* sky, whether the atmosphere be clear or hazy.

114. Clouds (*c*).—Either for clouds in detached masses, or in sheets with openings. Not to be used when the sky is overcast.

115. Fog (*f*).—Except among hills and in the cold weather in the damper parts of India, this symbol will not be much used. It is not to be used for mistiness, but only for such fogs as form over damp places in the evening.

116. Lightning (*l*).—Not to be used for the flashes that are sometimes seen to illumine the sky low down near the horizon. These, if noticed at all, may be entered as (lightning reflection).

117. Misty (*m*).—To be used for the dust haze so common throughout the dry season in the interior of India.

118. Overcast (*o*).—To be used when the sky is completely covered with pallio-cirrus or pallio-cumulus.

119. Passing showers (*p*).—Not for north-westers and similar storms, but for the case when showers, lasting for a few minutes, succeed each other with fine intervals.

120. Squally (*q*).—This initial, or the symbol for a strong wind, may be used for a north-wester, and that for a thunder storm may be used when, as is usually the case in Bengal, the north-wester ends in such a storm.

121. Visibility (*v*).—This symbol is very frequently misused. It has reference to the *transparency* of the atmosphere, and indicates that the details of distant objects can be seen with *unusual distinctness*. On the plains of India such a state is rarely experienced, except either immediately before, or immediately after, rain.

122. Hoar frost.—I include this in the symbols in general use, since hoar frost is tolerably common in the cold weather in certain parts of the Upper Provinces. It is simply dew deposited from air at or below the freezing point.

123. Coronas and halos.—These must be carefully distinguished. *Coronas* are very common, specially around the moon, and are produced by the rays passing through a thin layer of cloud. They are small circles around the luminary, as many as three concentric circles, with diameters in the ratio of 1 : 2 : 3, being sometimes seen at the same time. They are frequently coloured, red being the outside colour. These colours are not the pure colours of the spectrum, but rather those of the opal, or such as are seen in Newton's rings. They are interference, not refraction colours.

Halos are large circles of 46° and 92° in diameter, *i.e.*, the diameter of the circle is equal to either one-eighth or one-fourth the circumference of the horizon, or subtends either one-fourth or one-half the arc of the celestial vault. They are very rare phenomena, especially in India, but

have been occasionally seen from the Himalaya.[a] Solar halos are frequently accompanied by mock suns or *parhelia.*

The foregoing are of interest, rather as optical phenomena, than as affording important indications of processes of physical change in the state of the atmosphere. In this latter connection, the chief information afforded by them is the nature and consistency of the cloud on which they are projected; coronas being formed on water drops, halos only on snow crystals. Other optical phenomena of interest, as such, are, rainbows, fogbows or anthelia, mirage, &c., and the beautiful opal fringes of clouds, which may be witnessed not infrequently towards the evening, more especially in Bengal, in the hot weather and rains. All such phenomena are well worthy of observation and study; but, for information respecting them, the reader is referred to treatises of a less elementary and restricted character than the present.

124. Soft hail.—Small, soft, rounded, opaque, white pellets consisting of frozen snow.

125. Silver thaw.—Similar, in mode of formation, to hoar frost. A very dense deposit of long frozen needles, formed on the branches of trees.

126. Glazed frost.—When a thaw sets in, followed rapidly by a frost, the half-melted snow is refrozen, and covered by a film of ice presenting a glazed appearance and very slippery. This is termed "glazed-frost."

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[a] See, *e. g.*, an account of one witnessed by Captain W. Sherwill at Darjeeling in 1852, Journal of the Asiatic Society of Bengal, vol. xxiii, 1854, p. 49. A figure accompanies the description.

HOURS OF OBSERVATION.

127. Regulating conditions.—Instruments, such as the barograph, thermograph, anemograph, &c., that record continuously, afford, of course, the most perfect record that can be desired of the march of the several atmospheric phenomena; but even these require to be controlled by eye observations, since even the best machinery has, or may have, inherent faults, which require to be ascertained and their effects eliminated; and, moreover, it is not always practicable to give the instruments the same kind of exposure which is practised in the case of smaller instruments. This subject will be noticed presently. Next to self-registering instruments, hourly observations are the most effective; but they can be carried out continuously, only where a large establishment of observers is available. Even occasional hourly observations, such as those recorded on four days in each month at the second class stations of the Indian meteorological system, are, however, a very valuable adjunct to a meteorological register, and, wherever practicable, they should be taken. But in most cases the question is,—what is the smallest number of observations that will serve a useful purpose, and at what hours should they be recorded?

This latter question was discussed at the Vienna Conference, and certain sets of hours adopted alternatively, to be left to the choice of observers. But they were framed with a view to the conditions of extra-tropical countries, where the diurnal march of phenomena is less regular and dominant than in India, and they are not, for the most part, adapted to the conditions which obtain in this country. Moreover, it is of great importance to preserve uniformity, and it is, therefore, desirable that the same hours be observed at all stations. The hours should be such as will shew, as nearly as possible, the average range of the principal elements, and also afford the means of computing their mean values.

128. The adopted hours.—These conditions are best fulfilled by adopting the hours of 10h. and 16h. (10 A.M. and 4 P.M.) *mean local* time (not railway time) for reading the instruments. These hours are, on an average, those nearest to the maximum and minimum barometric pressure of the day, and this is the chief reason for selecting them. The mean of the two gives an approximation to the mean pressure of the day, while their difference is the approximate range. The temperatures are both above the mean temperature of the day, but by using self-registering maximum and minimum thermometers, the 10h. and 16h. temperatures afford data, which, together with the former, allow of a near approximation to the mean temperature of the day, when cor-

rected in the manner to be explained in the next chapter [§ 139]. A similar remark applies, with less accuracy, to the hygrometric elements, if a minimum wet-bulb thermometer be also used. The observations proper to be recorded at each of these hours, are—

At 10h.	At 16h.
Barometer.	Barometer.
Dry and wet bulb thermometers.	Dry and wet bulb thermometers.
Minimum dry and wet bulbs.	[a] Maximum thermometer.
Grass radiation thermometer.	[a] Sun thermometer.
Anemometer.	Anemometer.
Wind direction.	Wind direction.
Cloud proportion, kind and movement.	[a] Rain measurement.
General weather.	Cloud proportion, kind and movement.
	General weather.

General weather observations should, however, be made also in the intervals. Thus, the occurrence of dew or fog or hoar frost should be noted in the early morning; rain, or a thunder or dust storm, at the hour at which it occurs. Lunar coronas and halos must be looked for at night, &c. Meteorological observation can never be regarded as a mere mechanical performance. It requires intelligence, like most other work.

129. Additional hours.—If, in addition to the above, any other hours can be observed, the raingauge and maximum thermometers should be read at 18 hours. And, if an additional set of barometric and other readings can be taken, it is a very important addition to the register, to take them at 22 hours (10 P.M.).

130. Synoptic observations.—A system of synoptic observations has been started by General Mayer, of the U. S. Signal Service, which is now carried out in America, the British Isles and a great part of Europe, and which it is sought to extend all over the world. This is, to obtain observations made at the same absolute time, irrespective of the local time, all over the world. The Washington time is 7h. 35m. A.M. This is synchronous with Greenwich mean time 12h. 43m. The following are the corresponding hours of mean local time at some of the chief stations in India and its dependencies [b]:—

Kurrachee	17 h. 11m. P.M.	Bombay	17 h. 35m. P.M.
Deesa	17 „ 32 „ „	Poona	17 „ 40 „ „

[a] It is preferable to read these at 18h., as directed in the next paragraph.

[b] If the Madras time be deducted from that of the stations that follow, the remainder will shew how much the clock, set to local time at these stations, will be in advance of one set to railway time. And if, from Madras time, that of the stations that precede be deducted, the residue will shew how much a clock set to their local time will be behind one set to railway time.

Lahore	17 h. 40m. P.M.	Allahabad	18 h. 10m. P.M.
Belgaum	17 " 42 " "	Patna	18 " 24 " "
Bangalore	17 " 53 " "	Hazaribagh	18 " 25 " "
Roorkee	17 " 55 " "	Cuttack	18 " 27 " "
Agra	17 " 55 " "	Calcutta	18 " 36 " "
Trichinopoly	17 " 58 " "	Goalpara	18 " 46 " "
Nagpore	17 " 59 " "	Chittagong	18 " 50 " "
Jubbulpore	18 " 3 " "	Sibsagar	19 " 2 " "
Madras	18 " 4 " "	Rangoon	19 " 8 " "
Lucknow	18 " 7 " "		

The instruments to be observed are the barometer, dry and wet bulb thermometers, wind-vane, anemometer and raingauge; with observations on the quantity of the lower, and the direction of the upper clouds.

131. Importance of punctuality.—It cannot be too strongly impressed on observers that they must be strictly punctual to the hours assigned. The clock that regulates the observations must be kept at the true *local* time, and the observer should make it his business to be ready five minutes before the time, so that there may be no delay and irregularity. The whole process may take about five minutes, so that it is best to begin two minutes before the hour, and to read the instruments always in the same order. It depends on the Superintendents of Observatories to enforce regularity, seeing that laxity and unpunctuality are besetting sins, to which half-educated observers are especially liable. If an observer is unavoidably absent at the proper hour, it is better to omit the observations than to record them, perhaps, a quarter of an hour or twenty minutes after the proper time. A hiatus, however objectionable, is better than a deceptive entry.

132. Controlling observations.—Observations, the object of which is to control the registers of automatic instruments, (a thermograph, for instance,) should be taken about the times of maximum and minimum, and at as many intermediate periods as may be convenient. These should be repeated daily.

133. During storms.—During storms, the barometer is always greatly affected, and should be read, if possible, every 5 or 10 minutes, (together with the attached thermometer). The direction of the wind and the movements of the clouds should be observed also at short intervals; and, with the thermometer, hygrometer, and, if possible, the anemometer, recorded half-hourly or hourly.

When accompanied by very heavy rain, it is desirable to empty the raingauge, and to record its reading two or three times during the day.

REDUCTION OF OBSERVATIONS.

134. Reduction.—By the reduction of the observations is meant—*1st*, their correction for errors due to the imperfection of the instruments or their deviation from accepted standards; *2nd*, the elimination of effects which are not those we require to measure; *3rd*, the computation of certain elements which have not been observed directly, but which may be deduced from the observations; and *4thly*, the grouping of the results of the corrected observations in such a manner as may be most convenient for studying their relations to each other.

Under the *first* of these heads comes the correction of the index errors of barometers and thermometers, of the varying friction errors of anemometers, &c. Under the *second*, the correction of the barometer for cistern capacity and for temperature, and the deduction of the air temperature from that shewn by the sun thermometer, in order to obtain the differential effect of solar radiation. Under the *third*, the calculation of the barometric pressure at sea-level from the actual readings, and that of vapour tension and humidity from the readings of the dry and wet bulb thermometers. All these have been treated of, at sufficient length, under the respective headings of the several instruments and classes of observations; and it remains, therefore, only to deal with the 4th class of reductions, *viz.*, the grouping of the results; and these only to such an extent as is requisite for preparing the usual published statements of results. It is obvious that, for particular enquiries, the grouping of results may be indefinitely varied, and for such cases no general rules can be laid down: the intelligence of the investigator is then the only possible guide.

The most common form of grouping observations for publication is to give them as *mean* values for a day, month or year, with their extremes and range of variation.

135. Definition of mean values.—In ordinary language a *mean* is simply the arithmetical average of a number of specified values; but, as used in meteorological registers, something more than this is generally implied. It is not merely the average of the observations, but either the average of a *whole* day, a *whole* month or a *whole* year, and is understood to express the average value of *all* the variations that an element (such as pressure, temperature, &c.) undergoes from the beginning to

Figure 14. Diurnal curve of temperature.

the end of such period. To illustrate this geometrically:—suppose the line A B to represent a fixed temperature, say 70°, and the parallel horizontal lines above it represent successive increments of 1°. Let the vertical lines represent successive hours from midnight to midnight, and let us mark off on each of these a height representing the exact temperature of that hour. Draw a curved line through all these points, and it will represent the course of the changes of temperature throughout the day. The *mean temperature* of the day, so represented, will be the average, (not only of the hour lines represented, but also) of an infinite number of other vertical lines between them. Each of these being an ordinate of the curve, the mean temperature is represented by the mean or average ordinate of the whole curve. It is a line *such* that, if we draw a rectangle of *that* height on the base A B, the area of this rectangle shall be exactly equal to the area of the curved figure.

In order to ascertain this with great accuracy, it would be necessary to obtain a continuous trace of the temperature by some form of thermograph, and to measure the area comprehended between the curve and a fiducial base line. But for all practical purposes, it is quite sufficient to record observations at short and equal intervals of time, (generally an hour,) and to take the average of the whole. This was the practice at several first class observatories before the invention of self-recording instruments, and is still so at Calcutta. But it is very laborious, and would be impracticable where there is not a considerable staff of observers; and, therefore, various expedients are resorted to, to obtain something near this result from a smaller number of observations. It is, however, by no means a matter of indifference what observations we take and how we treat them. For instance, it is usual to observe the temperature at 10 A.M. and 4 P.M.; but, since at both these hours the warmth of the air is above the average of the twenty-four hours, the mean of these two observations would be much higher than the average which is required. The highest and lowest temperatures are also generally registered, but the mean of these is generally too high; since, as a general rule, the temperature ranges below the average longer than it ranges above it. Moreover, since the variation curves of pressure, tem-

perature, vapour tension, humidity, &c., are all different, a method that is applicable in one case is by no means so in another.

136. Method of six-hourly observations.—A method which, in principle, is similar to that of hourly observations, and, though inferior to it, gives results not very far from a true mean in the case of such elements as temperature, pressure, &c., is, to record observations four times daily, at equal intervals of six hours; and to take their average. The best hours for the purpose are 4 and 10 A.M. and P.M. Whenever this plan can be followed, *the proper hours being punctually adhered to*, it is the best substitute for continuous (autographic) or hourly registration; but, if this be not the case,—and it requires the stimulus of a deeper interest or a stronger sense of duty than is often to be met with to carry on such a system punctually and regularly,—it is better to content ourselves with methods less accurate in principle, but the conditions of which are more strictly fulfilled in practice.

137. Empirical methods.—These are very various. In order to apply them, we must first have ascertained the normal law of the variation, either from continuous registration, or from observations taken at short and equal intervals throughout the period of which the mean is required. This being known, (in the case of the diurnal period, for instance,) we know also how far a series of observations recorded at any given hour are *on an average* above or below the mean required; and, at least, twice every day the element in question is at its average value. The hours of average value are not, however, the same at different times of year, and an equally good result can be obtained by selecting hours that are otherwise convenient, and applying an average correction, which must be determined from the law of the variation. The method now adopted in the Meteorological Department is one devised by Mr. Pogson, and may be termed the method of range factors.

138. Pogson's range factors for pressure.—For the barometer, the use of these may be best explained by an example. Let it be required to determine the mean atmospheric pressure of any day from two observations of the barometer recorded at 10 A.M. and 4 P.M. at Házáribágh in the month of July. The average daily range of the barometer in this month at Házáribágh between 10 A.M. and 4. P.M. has been found to be ·0679 on the average of seven years. The 10-hour reading, on the same average, is ·0273 above the mean of the 24-hour, and the 4 P.M. readings ·0406 below it. The normal corrections for those hours (taking 3 decimals only) are, therefore, for 10 hours —·027 and for 16 hours +·041. Dividing each of these by the range, we have —0·40 for the 10-hour factor, and +0·60 for the 16-hour factor. These are constant values for that place and the month in question.

On the 8th July the reduced readings of the barometer at 10 hours

and 16 hours were 27·721 and 27·609. Their difference, or the range for that day, is 0·112. Multiplying this by the factors above determined, we have —·045 as the correction for the 10-hour reading and + ·067 for the 16-hour reading. Applying these to the readings, we obtain—

10-h. reading .	27·721	16-h. reading .	27·609
Correction . .	—·045	Correction . .	+·067
Mean of day .	27·676	Mean of day .	27·676

which is the adopted value: or we may take the *mean* of the two factors as the constant factor for the *mean* of the observations made at the two hours at the time and place specified, and proceed to apply a correction to the *mean* of the two readings, thus:—

10-h. factor . .	—0·40	10-h. reading .	27·721
16-h. „ . .	+0·60	16-h. „ . .	27·609
Mean . .	+0·10	Mean . .	27·665
Range . .	0·112	Correction . .	+0·011
Correction . .	+0·011	Corrected mean .	27·676

The greater the number of readings to which this process is applied, the smaller is the probable error of the result, provided the intervals between the readings are not too small.

139. Factors for temperature.—The readings of temperature, ordinarily recorded, are the maximum and minimum, the 10-hour and 16-hour readings. The maximum and minimum readings are used to determine the range, and the mean of the minimum, 10-hour, and 16-hour readings is corrected by a mean factor. At many stations, in certain months of the year, the maximum is so nearly the same as the 16-hour reading, and occurs so nearly at the same time, that to include it would give undue weight to the afternoon temperature. Let the mean factor for the three readings be +·05, and let the readings of the maximum, minimum, 10-hour and 16-hour be respectively 89°, 72°·5, 83°·5 and 86°. Then proceed as follows:—

Maximum . . .	89·0	Minimum . .	72·5
Minimum . . .	72·5	10-h. reading . .	83·5
		16-h. reading . .	86·0
Range . . .	16·5		
Factor . . .	+·05	Mean . . .	80·7
		Correction . .	+0·8
Correction . .	+0·8		
		Corrected mean .	81·5

140. Factors for the wet-bulb thermometers.—To obtain the mean of the wet-bulb readings, proceed in the same manner as for temperature, with this difference: that, instead of deducing the range from the difference of the maximum and minimum thermometers, the difference of the 16-hour and minimum readings are taken, thus—

16-h. reading . .	66·6	Minimum . .	58·0
Minimum . .	58·0	10-h. reading . .	71·4
	——	16-h. reading . .	66·6
Range . .	8·6		——
Factor . .	+·08	Mean . .	65·3
	——	Correction . .	+0·7
Correction . .	+0·7		——
	——	Corrected mean .	66·0

In all cases, the factors are, of course, computed originally from mean average readings, homologous with those to which they are to be applied.

141. Computation of mean vapour tension, humidity, &c.—Although not theoretically accurate, an approximate mean diurnal value of these elements, when the range is not very great, may be deduced from the corrected daily means of the dry and wet bulb temperatures, using these means as arguments, and taking the corresponding values out of the table used for the individual observations.

142. Determination of factors.—There are already on record the diurnal curves of pressure for Calcutta, Madras, Bombay, Lucknow, Trevandrum, Dodabetta and Simla, and those of Házáribágh, Patna, Goalpára, and some other stations will shortly be published. Hourly observations are now taken at several other stations in various parts of India, and eventually, from one or other of these, factors may be deduced which will be applicable to any station in India. Some special knowledge and judgment are required to determine which of these is to be selected in each case.

In general, the proper factors for a station will be furnished by the Meteorological office.

143. Monthly and annual mean.—The above description has reference chiefly to the computation of diurnal mean values. It is not often that any such expedients need be resorted to for obtaining annual or monthly means; although, *mutandis mutatis*, a similar course may be followed in their case, if necessary. The monthly mean is the arithmetical mean of all the days in the month, and the annual mean that of all the days in the year. Less accurately, the annual mean is obtained by taking the mean of all the monthly means. This is, indeed, the method

commonly practised; but it is not rigorously accurate, since it assigns to February, with 28 days, an equal importance with January and other months of 31 days each.

144. Mean wind direction.—By this term is to be understood, strictly, the resultant of all the wind movements during the hour, day, month or year; that is to say, the direction and distance to which a particle of air has moved during the period; or rather would have moved, supposing that, at each instant of time, it had the same motion as the air acting on the wind-vane and anemometer. All these movements combined would, in general, give a very circuitous course, but the resultant is the straight line that joins the beginning and end of the path. It can be ascertained, with a near approach to accuracy, only by reducing the trace of an anemograph, such as Beckley's: but, wherever, as in the interior of India, the winds are not very variable, a rough, but useful, generalization may be obtained by tabulating the number of observations under each point of the compass, and deducing the resultant by means of Lambert's formula, in the following manner. Assigning to each wind point its angular value, counted from north through east to south and west, we have—

N.	= 0°	S.	= 180°
N. N. E.	= 22° 30′	S. S. W.	= 202° 30′
N. E.	= 45°	S. W.	= 225°
E. N. E.	= 67° 30′	W. S. W.	= 247° 30′
E.	= 90°	W.	= 270°
E. S. E.	= 112° 30′	W. N. W.	= 292° 30′
S. E.	= 135°	N. W.	= 305°
S. S. E.	= 157° 30′	N. N. W.	= 327° 30′

From a table of natural sines and cosines (or their logarithms,) take out the values of the sines and cosines of each wind point observed, and multiply each by the number of observations recorded under that point. Add together the several products of the sines and the cosines separately; having due regard to their algebraical signs, since + sines are east and —sines west, + cosines north, and — cosines south components. The sum of the sines divided by the sum of the cosines gives the tangent of the resultant direction; and the square root of the sum of their squares, divided by the whole number of observations and multiplied by 100, gives the excess percentage of observations in the direction of the resultant.

When an anemogram which shews the distance travelled by the wind in each direction is thus treated, the proceeding is modified. The trace is first measured off and tabulated under as many points as may be found convenient, the number of *miles* recorded in each direction being entered under its proper point. The calculation is then proceeded with as above

described, the total number of miles under each point being used as the multiplier, instead of the number of observations, and the square root of the sum of the squares of the summed sines and cosines gives at once the number of miles travelled in the direction of the resultant.

145. Bessel's interpolation formula.—This formula is now so extensively used in the reduction of meteorological observations, that any description of methods of reduction would be very imperfect without some account of its use and application. Suppose the object be to ascertain the most probable course and law of the diurnal oscillation of the barometer at a given station, and let a series of hourly observations be undertaken for that purpose. Since this oscillation, which is regularly recurrent, is combined with a number of changes of pressure which are irregular and non-periodic, a single day's readings when projected in a curve will give some such irregular figure as that in the accompanying woodcut. If the observations are repeated for several days in succession, the greater irregularities of the individual curves will tend to neutralize each other, and something more like an evenly regular curve will begin to disclose itself in the figure which is given by the average of the whole. But completely to eliminate all irregularities would require the observations to be carried on for some years, and in certain cases very much longer. Now Bessel's formula affords the means of ascertaining the probable form of the curve from a comparatively moderate amount of data, and enables us to eliminate at once all such minor irregularities as affect small portions of the curve only.

Figure 15. [a]Curve of hourly barometric observations.

The fundamental principle of the method is this,—that the march of every phenomenon that goes through a regular cycle in a given fixed period, after which all its phases are repeated again and again in the same order and with the same magnitude, may be conceived as made up of elements, of which one is constant; another, during the cycle, goes *once* through all the variations of magnitude, positive and negative, represented by the sines of the regularly increasing arc of a circle,

[a] This curve is plotted from an actual register at Jubbulpore, and is more regular than usual.

of which the maximum value of that element is the radius; another of different magnitude goes *twice* through a similar revolution; a third three times, and so on. And thus, if we determine from observation the maximum numerical value of each of these elements, and also that phase of its revolution, at which it is at some fixed moment, (for instance, at midnight in the case of the diurnal cycle of a phenomenon), we can compute the value of the whole phenomenon at any other instant in the cycle, counting the time from midnight, at the rate of 15° of arc for each hour for the first periodical element, 30° for the second, 45° for the third, and so on; and then taking the sum of the whole and of the constant element.

Thus, then, let M represent the constant element, U', U'', U''' the maximum values of the first, second and third periodical elements, and u', u'', u''' the arcs which determine the phases of the several elements at midnight, measured from the zero point of arcs and sines in each of the corresponding circles. Then, if x be the value of the whole phenomenon at midnight—

$$x = M + U' \sin. u' + U'' \sin. u'' + U''' \sin. u''', \text{ \&c.}$$

And if x' is the value at any epoch n hours later, (n being any value whatever, integral or fractional) counted from midnight—

$$(1). \quad x' = M + U' \sin. (n15^\circ + u') + U'' \sin. (n30^\circ + u'') + U''' \sin. (n\,45^\circ + u'''), \text{ \&c.}$$

The formula will contain as many terms as there are elements computed. The number of these may be varied at the judgment of the computer; generally, it is found that, after the first three or four terms, the co-efficients become so small that they may be neglected without appreciably affecting the result.

The probable value of the constant co-efficients has been determined by Bessel, by the method of least squares; and the demonstration will be found in the original paper in Schuhmacher's *Astronomische Nachrichten*, and in the translation published by Mr. R. H. Scott as Appendix IV to the Quarterly Weather Reports of the Meteorological Office, London, for 1870; also in the Introduction to Schmidt's Meteorologie. The practical application is as follows;—

Let the subject of investigation be the diurnal variation of temperature; and suppose that, having recorded hourly readings on a sufficient number of days to eliminate all the greater irregularities, we obtain as the means, for each consecutive hour, counted from midnight, the values s_0, s_1, s_2, s_3, s_4, *&c.* . . . . s_{23}. Adding the whole together and taking their mean, we obtain the constant term M, which is the mean temperature of the day.

Then proceed to compute out the values of $U' \sin. u'$, $U' \cos. u'$, &c., by the following formulæ :—

$$U' \sin. u' = {}^1/_{12} [s_0 - s_{12} + (s_1 - s_{11} - s_{13} + s_{23}) \cos. 15^\circ +$$
$$(s_2 - s_{10} - s_{14} + s_{22}) \cos. 30^\circ + (s_3 - s_9 - s_{15} + s_{21}) \cos. 45^\circ +$$
$$(s_4 - s_8 - s_{16} + s_{20}) \cos. 60^\circ + (s_5 - s_7 - s_{17} + s_{19}) \cos. 75^\circ].$$
$$U' \cos. u' = {}^1/_{12} [(s_1 + s_{11} - s_{13} - s_{23}) \sin. 15^\circ + (s_2 + s_{10} - s_{14} - s_{22}) \sin. 30^\circ +$$
$$(s_3 + s_9 - s_{15} - s_{21}) \sin. 45^\circ + (s_4 + s_8 - s_{16} - s_{20}) \sin. 60^\circ +$$
$$(s_5 + s_7 - s_{17} - s_{19}) \sin. 75^\circ + s_6 - s_{18}].$$

whence $\dfrac{U' \sin. u'}{U' \cos. u'} = \text{tang. } u'$

The angle or arc u' corresponding to the value $\text{tang. } u'$ can be looked out in any table of trigonometrical constants, and, taking $\sin. u'$ from the same table, $\dfrac{U' \sin. u'}{\sin. u'} = U'$. The co-efficients of the next term are found by the following formulæ :—

$$U'' \sin. u'' = {}^1/_{12} [s_0 - s_6 + s_{12} - s_{18} +$$
$$(s_1 - s_5 - s_7 + s_{11} + s_{13} - s_{17} - s_{19} + s_{23}) \cos. 30^\circ +$$
$$(s_2 - s_4 - s_8 + s_{10} + s_{14} - s_{16} - s_{20} + s_{22}) \cos. 60^\circ].$$
$$U'' \cos. u'' = {}^1/_{12} [(s_1 + s_5 - s_7 - s_{11} + s_{13} + s_{17} - s_{19} - s_{23}) \sin. 30^\circ +$$
$$(s_2 + s_4 - s_8 - s_{10} + s_{14} + s_{16} - s_{20} - s_{22}) \sin. 60^\circ +$$
$$s_3 - s_9 + s_{15} - s_{21}]$$

from which, as before, we obtain—

$$\frac{U'' \sin. u''}{U'' \cos. u''} = \text{tang. } u'' \text{ and } \frac{U'' \sin. u''}{\sin. u''} = U''.$$

The values of U''' and u''' are given by the formulæ—

$$U''' \sin. \mu''' = {}^1/_{12} [s_0 - s_4 + s_8 - s_{12} + s_{16} - s_{20} +$$
$$(s_1 - s_3 - s_5 + s_7 + s_9 - s_{11} - s_{13} + s_{15} +$$
$$s_{17} - s_{19} - s_{21} + s_{23}) \cos. 45^\circ].$$
$$U''' \cos. u''' = {}^1/_{12} [(s_1 + s_3 - s_5 - s_7 + s_9 + s_{11} - s_{13} - s_{15} + s_{17} +$$
$$s_{19} - s_{21} - s_{23}) \sin. 45^\circ + s_2 - s_6 + s_{10} - s_{14} + s_{18} - s_{22}].$$

from which U''' and u''' are found as before; and if a fourth term be required—

$$U'''' \sin. \mu'''' = {}^1/_{12} [s_0 - s_3 + s_6 - s_9 + s_{12} - s_{15} + s_{18} - s_{21} +$$
$$(s_1 - s_2 - s_4 + s_5 + s_7 - s_8 - s_{10} + s_{11} + s_{13} - s_{14} - s_{16} + s_{17} +$$
$$s_{19} - s_{20} - s_{22} + s_{23}) \cos. 60^\circ].$$
$$U'''' \cos. u'''' = {}^1/_{12} (s_1 + s_2 - s_4 - s_5 + s_7 + s_8 - s_{10} - s_{11} + s_{13} + s_{14} - s_{16} - s_{17} +$$
$$s_{19} + s_{20} - s_{22} - s_{23}) \sin. 60^\circ].$$

From a careful study of the above, the reader will readily gather the principle which will enable him to construct formulæ for any required number of terms. In applying the formula to other cases, such as the computation of the annual curve from 12 monthly means, or the variation of the wind co-ordinates from observations tabulated to eight or sixteen points, or, to speak generally, from any number m sets of observations, which divide the whole cycle into m equal parts, it is

to be observed that the fractional co-efficient represented above by $\frac{1}{12}$ is always $\frac{2}{m}$; therefore $\frac{1}{6}$ for 12 sets; and $\frac{1}{4}$ for 8; and that the arcs which are 15° and multiples of 15° in the above formulæ are replaced by $\frac{360°}{m}$ and its multiples.

The values of the constant co-efficients in formula (1) having been found, those of the whole phenomenon may then be calculated by the formula for each hour (or other interval) in succession, by giving to n its consecutive values 1, 2, 3, &c., or any others that may be desired.

The following example will serve as an exercise to familiarize the student with the use of the formula.

The hourly and six-hourly observations of temperature at Yarkand in the spring months March, April and May, after some minor corrections, gave the following average values :—

Hour.	Temp.	Hour.	Temp.	Hour.	Temp.	Hour.	Temp.
Mid. ...	54·6	6 ...	49·6	Noon ...	71·8	18 ...	65·3
1 ...	53·1	7 ...	53·6	13 ...	72·2	19 ...	62·2
2 ...	51·7	8 ...	58·3	14 ...	72·7	20 ...	60·1
3 ...	50·3	9 ...	63·3	15 ...	72·3	21 ...	58·7
4 ...	49·4	10 ...	67·5	16 ...	71·4	22 ...	57·3
5 ...	48·9	11 ...	69·5	17 ...	68·6	23 ...	55·9

The mean of the whole, $M = 60·76$

$$
\begin{array}{lr}
54·6 - 71·8 \qquad\qquad = & -17·2 \\
(53·1 - 69·5 - 72·2 + 55·9)\ cos.\ 15° = & -31·59 \\
(51·7 - 67·5 - 72·7 + 57·3)\ cos.\ 30° = & -27·02 \\
(50·3 - 63·3 - 72·3 + 58·7)\ cos.\ 45° = & -18·81 \\
(49·4 - 58·3 - 71·4 + 60·1)\ cos.\ 60° = & -10·10 \\
(48·9 - 53·6 - 68·6 + 62·2)\ cos.\ 75° = & -2·87 \\
\hline
12\ ) & -107·59 \\
U'\ sin.\ u' = & -8·966
\end{array}
$$

$$
\begin{array}{lr}
(53·1 + 69·5 - 72·2 - 55·9)\ sin.\ 15° = & -1·52 \\
(51·7 + 67·5 - 72·7 - 57·3)\ sin.\ 30° = & -5·40 \\
(50·3 + 63·3 - 72·3 - 58·7)\ sin.\ 45° = & -12·30 \\
(49·4 + 58·3 - 71·4 - 60·1)\ sin.\ 60° = & -20·61 \\
(48·9 + 53·6 - 68·6 - 62·2)\ sin.\ 75° = & -27·34 \\
49·6 - 65·3 \qquad\qquad = & -15·70 \\
\hline
12\ ) & -82·87 \\
U'\ cos.\ u' = & -6·906
\end{array}
$$

$$\frac{-8}{-6.906} \quad 1.2994 = tang.\ 232^\circ\ 25'$$

$$\frac{-8.966}{sin.\ 232^\circ\ 25'} \quad 11.32.$$

$$\therefore \quad U' = 11.32\ u' = 232^\circ\ 25'.$$

Computing U'' and u'', U''' and u''', U'''' and u'''' in a similar manner by their respective formulæ, we obtain—

$$U'' = 2.643 \text{ and } u'' = 84^\circ\ 21'$$
$$U''' = 0.911 \quad ,, \quad u''' = 36^\circ\ 45'$$
$$U'''' = 0.567 \quad ,, \quad u'''' = 234^\circ\ 11'$$

and substituting these values in (1)—

$$x' = 60.76 + 11.32\ sin.\ (n\ 15^\circ + 232^\circ\ 25') + 2.64\ sin.\ (n\ 30^\circ + 84^\circ\ 21') + 0.91\ sin.\ (n\ 45^\circ + 36^\circ\ 45') + 0.57\ sin.\ (n\ 60^\circ + 234^\circ\ 11')$$

In the next place we proceed to compute the probable hourly values of the temperature. By the formula for midnight we have simply—

$$x_0 = M + U'\ sin.\ u' + U''\ sin.\ u'' + U'''\ sin.\ u''' + U''''\ sin.\ u''''$$
$$= 60.76 - 8.97 + 2.63 + .54 - .46 = 54.51.$$

For 1 A.M.—

$$n = 1$$

$$\therefore x_1 = 60.76 + 11.32\ sin.\ (15^\circ + 232^\circ\ 25') + 2.64\ sin.\ (30^\circ + 84^\circ 21') + 0.91\ sin.\ (45^\circ + 36^\circ\ 45') + 0.57\ sin.\ (60^\circ + 234^\circ\ 11')$$

which, being calculated out, gives—

$$60.76 - 7.66 = 53.10.$$

For 2 A.M.—

$$n = 2$$

$$\therefore x_2 = 60.76 + 11.32\ sin.\ (30^\circ + 232^\circ\ 25') + 2.64\ sin.\ (60^\circ + 84^\circ\ 21') + 0.91\ sin.\ (90^\circ + 36^\circ\ 45') + 0.57\ sin.\ (120^\circ + 234^\circ\ 11')$$

which gives—

$$x_2 = 60.76 - 9.01 = 51.75.$$

Having thus computed all the values x_3, x_4, &c., up to x_{23}, let us arrange them in parallel columns with the original means, and take the differences in a third column—

Hour.	$s.$	$x.$	Difference.	Hour.	$s.$	$x.$	Difference.
Mid.	54·6	54·51	— 0·09	6	49·6	50·04	+ 0·44
1	53·1	53·10	0	7	53·6	53·36	— 0·24
2	51·7	51·75	+ 0·05	8	58·3	58·22	— 0·08
3	50·3	50·39	+ 0·09	9	63·3	63·32	+ 0·02
4	49·4	49·18	— 0·22	10	67·5	67·42	— 0·08
5	48·9	48·78	— 0·12	11	69·5	69·98	+ 0·48

Hour.	*s*.	*x*.	Difference.	Hour.	*s*.	*x*.	Difference.
Noon.	71·8	71·35	—0·45	18	65·3	65·30	0
13	72·2	72·20	0	19	62·2	62·30	+ 0·10
14	72·7	72·73	+ 0·03	20	60·1	60·10	0
15	72·3	72·57	+ 0·27	21	58·7	58·60	—0·10
16	71·4	71·20	—0·20	22	57·3	57·32	+ 0·02
17	68·6	68·58	—0·02	23	55·9	55·96	+ 0·06

These differences or errors are not larger than might be expected, regard being had to the comparatively moderate number of the observations from which the means are derived; and, moreover, they present that irregularity which characterizes them as probable errors. We may, therefore, consider the computed values x_0, x_1, &c., as the most probable temperatures.

As here described, the calculation may seem somewhat tedious, but in practice it is very quickly carried out with the help of logarithms. After a little practice, a fairly good computer will calculate the whole in an hour or less.

146. Instants of maxima and minima.—By the help of this formula the instants at which any phenomenon attains its maximum and minimum values, and these values themselves may be ascertained with great accuracy. It follows from algebraical reasoning, that x will have either a maximum or a minimum value, when the value of n is such that

$$(2)\quad U' \cos. (n\ 15^\circ + u') + 2\ U'' \cos. (n\ 30^\circ + u'') + = 0$$
$$3\,U''' \cos. (n\ 45^\circ + u''')\ \&c.$$

Dr. Jelinek has given the following method of determining this value very expeditiously, when the values of x_0, x_1, x_2, &c., have been calculated out. These computed values shew very nearly when a phenomenon reaches its maximum or minimum; for instance, in the above example, the minimum temperature is clearly a little before 5h. and the maximum a little after 14h. Let us take out from the table the values at 5h. and 14h., and those of the even hours before and after, and thence obtain the first and second differences Δ_1 Δ_2—

	Minimum.				*Maximum.*			
	49·18	48·78		50·04	72·20	72·73		72·57
Δ_1	—0·40		+1·26			+0·53	—0·16	
Δ_2		+1·66				—0·69		

Now, by the method of differences, if we start with the value at the middle hour of the triad, *i. e.*, the even hour nearest to minimum (or maximum), the value at any *later* instant t (t being less than 1 hour) will be found by the formula—

$$A + t\Delta_1{}' + \frac{t(t-1)}{2}\Delta_2 + \frac{(t+1)\,t\,(t-1)}{2\cdot 3}\Delta_3{}' + \&c.,$$

in which A is the initial value, $\Delta_1{}'$ the first subsequent difference, Δ_2 the second coincident difference, &c., at the same hour. The value of this equation will reach a minimum (or maximum) value when its differential coefficient becomes zero, that is, when

(3) $\Delta_1{}' + (t-\frac{1}{2})\Delta_2 + \&c., = 0$

Now, taking the first and second, and neglecting the higher differences, we obtain from this equation an approximate value of t. Let us call this value t';

$$t' = \tfrac{1}{2} - \frac{\Delta_1{}'}{\Delta_2}$$

and substituting for $\Delta_1{}'$ and Δ_2 the values, found above for the hour nearest the minimum—

$$t' = 0\cdot5 - \frac{1\cdot26}{1\cdot66} = -\ 0\cdot26\text{hour} = 15\text{min. } 36\text{sec. earlier than 5h.};$$

and with the values for that nearest the maximum—

$$t' = 0\cdot5 - \left(\frac{-0\cdot16}{-0\cdot69}\right) = 0\cdot27\text{hour} = 16\text{min. } 12\text{sec. later than 16h.}$$

By this first approximation the minimum temperature occurs at 4 hours 44 minutes, and the maximum at 14 hours 16 minutes.

In order to obtain a second and closer approximation for the minimum (the maximum may be treated in like manner), convert 4 hours 44min. into degrees and min. of arc; substitute it and its multiples for $n15°$ and its multiples in equation (2), and calculate out the numerical value of the equation. It will not be 0, since t' is not exactly the true moment of minimum. Instead of this, we find—

$$11\cdot32\cos(71°6'+232°25') + 5\cdot286\cos(142°12'+84°21') + = -0\cdot4285$$
$$2\cdot733\cos(213°18'+36°45') + 2\cdot268\cos(284°24'+234°11')$$

Let us call this value f. Now the expression in equation (2), if multiplied by $dn\ \sin.1''$ will represent the increment (or decrement) of temperature that ensues in the time that $n15°$ increases by dn seconds of arc. If we assume that this rate of increment remains constant for an hour, then, since $dn = 15° = 54{,}000$ seconds, and $dn\ \sin.1'' = 54{,}000\ \sin.1'' = 0\cdot2618$,

$$0\cdot2618f = -\ (0\cdot4285 \times 0\cdot2618)$$

is the change of temperature, which, on this assumption, would take place in an hour, if it continued at the same rate of change as at the instant t' found by the first approximation. The expression—

$$\Delta_1{}' + (t'-\tfrac{1}{2})\ \Delta_2 +, \&c.,$$

has the same signification; and therefore

$$\Delta_1' + (t' - \tfrac{1}{2})\,\Delta_2 + \&c. = 0{\cdot}2618f$$

$$t' - \frac{0{\cdot}2618f}{\Delta_2} = \tfrac{1}{2} - \frac{\Delta_1'}{\Delta_2} -, \&c., = t$$

wherein t is the second approximation. Hence—

$$\frac{0{\cdot}2618f}{\Delta_2} = \frac{(0{\cdot}2618 \times -0{\cdot}4285)}{1{\cdot}66} = - \cdot 0676$$

is the correction to be deducted from t' (with due regard to the algebraical sign) in order to obtain t the second approximation—

$$-0{\cdot}26-(-{\cdot}0676) = -\ 0{\cdot}1924 = -11\text{min. } 33\text{sec.}$$

and, neglecting seconds, the instant of minimum temperature is thus found to be 5h. *less* 12min. = 4h. 48min. The process may, of course, be repeated to obtain a third approximation, but there can be no practical object in aiming at greater precision than is already attained by the second approximation as above.

Having ascertained with sufficient exactness the instants of maximum or minimum by the above methods, the value of the maximum and minimum, and consequently the range of the variation, may be easily found: convert the time of their occurrence into degrees of arc, and substitute this value for n 15°, &c., in equation (1), page 72. The resulting values will be those of the maximum and minimum, and their difference will be the range.

REGISTRATION.

147. Forms.—Specimens of the principal forms of register in use in the Indian Meteorological Department are appended. Those marked A. and B. are for general use at all stations at which observations are recorded regularly at 10*h*. and 16*h*., the rain-gauge and maximum thermometers being read also at 18*h*. Those marked E. and F. are for hourly observations.

148. Form B.—This is for recording the readings as made, *without any correction or reduction*. The name of the station is to be entered at the top of the form, and the distinguishing numbers of the several instruments in the first column after their names. The entries for the first and [redacted] (in February the [redacted]), day of the month should begin a new form; and since each form contains the register of eight days, four forms will be required for each month, the columns for one or two days (in February two or three days), being left unfilled in the last form. The name of the month, together with the ordinal number of the day, is to be entered in the first blank space at the top: on the remaining days the ordinal number alone will suffice. The instruments to be read at the hours directed in §§ 128 and 129.

149. Form A.—This is for the reduced and corrected readings, the half-monthly and monthly means, &c.; and each form is intended to receive the register for one month. The name of the station, that of the month, the latitude and longitude, the elevation of the barometer cistern above sea-level and the distance of the station in a direct line from the sea, are to be entered at the top of each form in a neat *round hand*. The smaller entries in small hand, *viz.*:—

1st.—The place in which the thermometers are exposed, as "thatched shed open all round," or "louvred shed of plank work," or "north verandah," &c., and the height of the frame or cage above the ground.

2nd.—The mode in which the hygrometric elements have been computed, such as "Met. Dep. Tables IV, V and XII," "Apjohn's formula," "August's formula," "Glaisher's tables," &c.

3rd.—The source from which the hour corrections have been obtained, thus, "range factors from local hourly observations," "range factors from Calcutta hourly observations," "range factors from local six-hourly observations," &c.

4th.—The height of the solar radiation thermometer above the ground.

5th.—That of the grass radiation thermometer. And after the word "ground" should be added such words as "over thick green grass," "over dry grass," "over thinly-growing tufted grass," "over bare ground," "over black woollen cloth," &c. In some cases this entry will vary with the time of year.

6th.—The height of the *mouth* of the rain-gauge above the general ground level.

7th.—A brief description of the position of the anemometer, such as "a post fixed in the ground," "post three feet high on north-east corner of terraced roof," "post 5 feet high on ridge of roof of dispensary, &c." Also in all cases the height of the anemometer cups above the ground.

In the first column the days of the week to be designated by their initials. For that of Sunday the sun symbol ⊙ may be substituted. In February the first half month should close on the 14th, and the figures of the second half should be altered.

Columns 1 *to* 6.—Enter, before the word 'barometer' at the top, an abbreviated description of the kind of instrument in use, such as "Marine K. P." (Marine Kew Principle), "Mountain Fort." (Mountain, Fortin's principle), "Stand. Fort." (Standard, Fortin's principle). Also the distinguishing number, and the initials or first syllable of the maker's name as "946 Cas." (Casella), "734 N. and Z." (Negretti and Zambra), &c. In columns 2 and 3 enter the barometric readings at 10h. and 16h., corrected and reduced (§§ 12, 14), in column 1 their difference, in column 4 the correction for the day (§ 138), and in column 5 the corrected mean. In column 6 the mean corrected to sea-level (§ 15).

Columns 7 *to* 14.—Enter, at the top of the column, the distinguishing numbers of the maximum, minimum and the dry bulb of the hygrometer. In columns 7 and 9 the readings of the minimum and maximum thermometers corrected for index error, and in column 8 their difference. In columns 10 and 11 the corrected readings of the dry-bulb thermometer. In column 12, the correction obtained by multiplying the proper factor into the figures in column 8 (§ 139), and in column 13 the mean of the figures, in columns 7, 10 and 11 with the addition of the correction. Lastly, in column 14, the sea-level equivalent of the mean temperature, which is obtained by adding a constant correction to the values in column 13. In the case of hill stations column 14 is to be left blank.

Columns 15 *to* 19.—As the above, with the variations in the method of deducing the correction for hours, for the wet-bulb thermometers, described in § 140.

Columns 20 *to* 23.—The entries in column 20 are the vapour tensions computed or taken out of the proper table [§ 70] from the readings of the dry and wet bulb minimum thermometers in columns 7 and 15; in columns 21 and 22 from the readings of the hygrometer in columns 10, 11, 16 and 17; and in column 23 from the means in columns 13 and 19.

Columns 24 *to* 27.—As the above, from the proper humidity tables (§ 73).

Columns 28 *to* 31.—From the vapour tensions in the corresponding columns 20 to 23, and with the temperatures in columns 7, 10, 11 and 13, the weight of vapour computed from Table XII.

Columns 32 *and* 33.—In column 32, the corrected reading of the solar radiation thermometer, and in column 33 the difference of this and the corrected maximum shade temperature in column 9.

Columns 34 *and* 35.—The corrected reading of the grass minimum thermometer and the difference of this and the reading of the minimum shade thermometer in column 7.

Columns 36 *to* 38.—In column 36 the difference of the anemometer reading at 10h. of the day of record and at 16h. of the previous day. In 37 that of the 10h. and 16h. readings, and in 38 the sum of these two entries.

Columns 39 *and* 40.—The wind directions observed at 10h. and 16h. according to 16 points, indicated by the letters in § 83: care must be taken to enter '*c.*' for calm, when the anemometer is not moving at the time of observation.

Column 41.—The rain measured at 18h.

Columns 42 *to* 44.—The cloud proportion estimated at 10h. and 16h. (§ 99), and in column 44 the mean of the two. If there is no cloud, a zero '0' is to be entered; if no observation has been made, a '?'.

Columns 45 *to* 47.—Cloud symbols, Beaufort's initials and Vienna symbols, for which see § 112; noting that these cloud symbols are to be entered in printing capitals, thus C, except when double, as Ck. The Beaufort's initials in small italics. The hours at, or between, which any phenomenon occurs should be entered thus T K 13h.—16h., 6h. Such words as 'cool,' 'pleasant,' 'sultry,' &c., may well express the feelings of the observer and may be interesting to his friends; but they are not of importance in a meteorological register, and may be omitted with advantage.

Sums and means.—The sums and means of all the columns are to be entered at the foot of the form, except in the case of the wind direction, rain, columns 39, 40, 41 and weather symbols, &c., in columns 45 to 47. In the case of the wind direction, the space may be left blank, or the resultant computed by Lambert's formula (§ 144), may be inserted; in the case of the second, the sum only is required, and in that of the third the only summary possible would be a simple enumeration of the several symbols. This space, therefore, may be left blank. In taking the means of cloud proportion, the sum of each column is to be divided by the whole number of days in the month, notwithstanding that '0' may be entered on several days.

Maximum and minimum.—It is convenient when a month's register has been completed, to mark the highest and lowest value of each kind of phenomenon, by underscoring the entry with red ink.

150. Forms E and F.—These correspond respectively to Forms B and A above described, but are intended for hourly readings. They require no special description. The last column on Form F. is intended for the initials of the observers who take the several observations.

151. Neatness.—*A meteorological register should be kept with the same neatness as a merchant's ledger. Slovenliness and indistinctness in the entries are a tolerably sure indication that the work recorded has been of the same character.*

RULES FOR OBSERVERS AT GOVERNMENT OBSERVATORIES IN INDIA.

GENERAL.

1. *Punctuality.*—Take observations at the appointed hours [§§ 128, 129, 130] according to local mean time, not railway time. Keep the clock accurately regulated and begin to take the observations two minutes before the hour. Be punctual and accurate [§ 131].

2. In storms observe all instruments as frequently as possible, [§ 133].

3. Never allow of any break or discontinuity in the register, if it can *possibly* be avoided; specially in the raingauge observations. But if any such break is unavoidable, make no attempt to fill it by interpolation.

4. *Cleanliness.*—Every instrument is to be kept scrupulously clean. The feather of a quill or a soft brush may be used to dust the more delicate instruments; a soft cloth, slightly damped, to clean the glass of the larger instruments.

5. *Change of instruments.*—Every instrument differs from others of the same kind in *some* particulars: each has errors peculiar to it, and requires its own special corrections [§§ 11, 12, 26, 27, 51, 91]. If, therefore, any instrument be changed, *e. g.*, one thermometer substituted for another, report the fact by letter to the Meteorological Reporter, giving the number and description of the substituted instrument, and of that replaced, and enter the same at the foot of the register form, with the hour and date at which the substituted instrument was first observed.

6. *Change of position.*—The place and position of an instrument are *never* to be changed, unless the change is *absolutely necessary.* In the case of most instruments, the barometer and sun thermometer more especially, any change of place introduces a permanent change in the average readings of the instrument [§§ 15, 16]. If unavoidable, the Meteorological Reporter *is to be apprized of the proposed change beforehand;* and, when effected, the date and other particulars are to be reported to him, and also entered on the register.

BAROMETER.

7. *Unpacking and suspending.*—Take the barometer out of its case, cistern upwards. If on Fortin's principle, unscrew the milled headed screw at the bottom of the cistern [§ 4] one or two turns, then invert the barometer, *slowly* and *gently*, and suspend it to a strong nail or spike, at such a height that the 31-inch mark of the scale is about on the level of the eye of the observer.

8. *Verticality.*—When the barometer is suspended and before any reading from it is taken, ascertain that it is truly vertical by means of a plumb line, viewed both in front and from the side [§ 2].

9. *Place for barometer.*—The barometer must, as far as possible, be protected from all changes of temperature. A thermometer shed is the worst possible place for it. It should be in an inner room, where there is a good side light [§ 17].

10. The sun must never shine on it. The light should be from the side, not from the back or front, of the instrument. The 31-inch mark should be at the level of the observer's eye when standing upright. A sheet of white paper, or other white surface, well illuminated, should be behind the cistern and the top of the column [§ 17].

11. *Level.*—The level of the mercury surface of the cistern, above or below the nearest bench mark, is to be ascertained by spirit levelling. The readings of a barometer, the exact elevation of which is unknown, are of little use [§§ 15, 16].

12. The bench mark should be, if possible, one fixed by the spirit-levelling parties of the Great Trigonometrical Survey. Failing this, it may be one the height of which above sea level has been ascertained by the irrigation officers, railway engineers, or trigonometrically by the Great Trigonometrical Survey [§ 16].

13. At stations on the sea coast, the level may be referred to the mean half-tide level.

14. *Order of observation.*—First read the attached thermometer, and note the reading. Then regulate the cistern level [§ 4]. Next, adjust the vernier [§ 9], and take the reading, and finally look again at the attached thermometer to verify the first reading.

15. The vernier is to be read to the nearest thousandth of an inch.

16. *Night readings.*—Never place a lamp or candle near the barometer, but at a distance of not less than one foot.

17. Throw the light *on the paper* behind the cistern and column, while adjusting the cistern level and vernier.

18. *Injuries and accidents.*—Sometimes, on unpacking a barometer after a journey, a little mercury is found to have leaked from the cistern. But the barometer *may* be in good order. To ascertain this, test the vacuum cautiously [§ 18], then regulate the cistern level [§ 4]. If the vacuum is good, and the mercury touches the ivory stud, the instrument is probably in good order.

19. See that the cistern bottom (not the regulating screw) is screwed well home, and *never unscrew it.* Leaking from the cistern is frequently owing to the cistern bottom being loose.

20. Drops of mercury condensed in the Torricellian vacuum above the column, are of no importance, and do not affect the reading.

21. If the vacuum be imperfect, or any part of the barometer be broken, return the instrument for repair.

22. *Repacking.*—Always send barometers packed on a bamboo dooly, carried by two men [§ 19].

23. Detach the barometer from its suspension, screw up the mercury to the top of the cistern, then invert the instrument cautiously, and give the cistern screw another turn, but leave an air space about equal to the bowl of a teaspoon. Place in the case, cistern upwards, and take care that in carriage it is kept in this position.

THERMOMETERS AND HYGROMETERS.

24. *Suspension.*—Suspend the thermometers as shewn in the diagram, Plate I, so that the bulbs may be between 3 feet 9 inches and 4 feet 6 inches above the ground, and the wet and dry bulbs as far from each other as the frame will admit of. Expose them under a shed, of the form and dimensions shown in Plate I.

25. Never suspend thermometers for meteorological purposes in an office or dwelling-room. If no shed is available, suspend them on a frame standing (not against a wall) in a verandah having a northern aspect. But in such a position they will not shew the range of temperature [§ 35].

26. They must be protected, not only from direct sunlight, but also, as far as possible, from the radiation of surfaces strongly heated by the sun. But they should be freely exposed to the wind.

27. For the position of radiation thermometers, see §§ 46, 47, 51.

28. *Observations.*—Read thermometers as quickly as possible, taking care that the eye is *exactly* on the level of the top of the column if the thermometer is vertical, and exactly opposite (neither to right nor left of it) if horizontal. The smallest deviation introduces an error: [§ 28].

29. Do not bring the hand or face near the bulb, and do not bring a lamp at night time nearer than can be helped.

30. Read thermometers, by estimation, to the nearest tenth of a degree.

31. Before reading a minimum or other spirit thermometer, *always* examine the tube to see that there are no drops of spirit in the upper parts of the tube and no air bubbles in the spirit column and bulb. Especially look beneath the brass staple that fixes the tube and in the expansion at the top of the stem. If the column is not entire, reject the reading and restore the column *at once*, [§ 43].

32. After writing down the reading of a thermometer, look again at the instrument to check its accuracy.

33. *Wet-bulb thermometers.*—These must be freely exposed to the wind.

34. They must be kept clean, and free from encrustation. The muslin and thread to be washed at least once a week and renewed at least once a month.

35. If possible, use rain-water only, and store it for the purpose. In rainless regions, use distilled water if you can get it. If not, *boil* water well and long, and filter it before using it.

36. The muslin must fit closely to the bulb and not hang in folds. It must be thin and applied in one thickness only. To renew it, cut a piece about one inch square; wet it well, apply it to the bulb and draw it closely over it; tie it with a bundle of 8 or 10 clean and well-washed yarn threads, and cut off the free edges neatly.

37. When the wet bulb is below the freezing point, it must be dipped in water half an hour before the reading is taken, [§ 67].

38. *Radiation thermometers.*—The grass thermometer is especially liable to separation of the column. Always examine it before reading, and rectify it [§ 43] before re-exposing it. See Rule 31. If dew is deposited in the protecting tube, wipe it out with a piece of cotton on a wire.

39. Sun thermometers sometimes have a minute piece of the mercurial column (= 2 or 3 degrees) detached, and difficult to re-unite. In such cases measure the length it subtends in degrees, and add the amount to the reading, until you can get it to re-unite.

40. Sun thermometers on Phillip's principle [§ 39] are liable to lose the air speck which separates the index. In this case the instrument no longer acts as a maximum. This is easily detected, since the column under these circumstances contracts with every fall of temperature.

41. If the glass jacket of a sun thermometer is the least cracked, the instrument must be rejected.

42. Never change the place of exposure of a sun thermometer nor its height above the ground, if it can be avoided. If unavoidable, report the change and date of the removal.

43. Never leave a radiation thermometer exposed to hail. If a thunder storm is imminent, remove it to a place of safety till the storm is over.

44. *In case of accidents.*—If the dry-bulb thermometer be broken, take the readings of the maximum till it can be replaced, resetting it at each observation before taking the reading.

45. If the minimum in air be broken, read the standard *before sunrise* instead.

46. If the ordinary wet bulb be broken, take the *actual* reading of the minimum wet bulb.

47. If the minimum wet bulb be broken, take the reading of the ordinary wet bulb *before sunrise* instead.

RAINGAUGE.

48. *Position.*—Fix the gauge in an open place, as far as possible from trees, houses and other obstructions. It should in no case be within 30 paces of any building or tree [§ 81].

49. Bury the gauge or its stand *firmly* in the ground, leaving the mouth of the funnel one foot above the ground [§ 78].

50. *Hours of observation.*—Read and empty the gauge regularly at 18h.; during heavy rain more frequently, and so often as to incur no risk of loss by its running over. At telegraphing stations read the rain regularly at 10h. and 16h. likewise.

Measuring.—See that the measure-glass is empty before measuring. Place the measure-glass on a large dish, and pour the contents of the receiver into it slowly and carefully, to avoid spilling. The measure holds one inch.[a] If the receiver contain more than one inch, fill the former up to the one-inch mark. Then empty it and refill. Each entire filling represents one inch of rainfall. The last partial filling is read off on the graduation as tenths and hundredths.

52. If the measure of a Symon's gauge be broken, measure the rainfall in an apothecary's glass graduated to fluid ounces, and compute therefrom the rainfall as directed in § 78.

53. If the receiver of a raingauge leak, it may be repaired by an ordinary mechanic; but if the form of the rim of the receiving funnel is altered, if it be not *truly* circular (or *truly* square), the gauge registers falsely and is worse than useless.

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[a] The measure-glasses of some gauges hold half an inch only. In such cases the words *half inch* must be substituted for *inch* in this rule.

ANEMOMETER AND WIND-VANE.

54. *Choice of site and fixing.*—These instruments are to be fixed on the *highest point* of the house occupied by the observer, if the following conditions are fulfilled :—

(*a*).—If no trees loftier than the house are in the immediate neighbourhood.

(*b*).—If there be no much loftier house within 50 yards.

55. The vane and anemometer cups must not be less than four feet above the highest point of the roof.

56. The dial that shews the points of the compass, or the cross rods that shew the cardinal points (on a common vane), must be set truly, by the aid of an azimuth compass, to true (not magnetic) north.

57. *Setting up the 2-wheel anemometer.*—Screw the piece of gas pipe, which serves to carry the instrument, on an iron rod firmly bedded in brickwork, or clamp it to a stout post firmly fixed on the roof of the house; then screw on the dial box. It must be at a considerable height (not less than 20 or 30 feet) above the ground.

58. Before fixing the cup frame in place, unscrew and remove the brass nut, and the brass column on the top of the dial box. Oil the upper part of the spindle thoroughly, then replace the brass column, and screw it home. Place the cup frame on the spindle, so that when moving with the wind, the figures 1, 2, 3, 4, 5, on the *inner* scale of the dial, pass in that order under the fixed pointer.

59. *Setting up the 5-wheel anemometer.*—Procure a piece of wood 4 or 5 feet in length and 4 inches square, with one end planed, smooth and level. Secure it by strong iron clamps, in an upright position, to the brickwork of the parapet or wall of the observatory, and with the end at a proper height above the roof, and level (Rule 55). Screw the dial box of the anemometer on the smooth end, and further secure it by iron clamps over the flange. It must be not less than 20 feet above the ground.

60. Before fixing the cup frame, unscrew and remove the brass nut from the spindle, and the brass column on the top of the dial box; oil the upper part of the spindle thoroughly. Replace the brass column, and screw it home. Place the cup frame on the spindle in such a manner that, when set in motion by the wind, the figures on the several dials may pass beneath the pointers in their proper order, 1, 2, 3, &c.

61. *Reading the anemometer.*—For full directions, see §§ 92 and 94.

62. *Oiling.*—Oil the working parts of the vane, about once a month, with neatsfoot oil, but add the oil sparingly, leaving no excess to take

up dust, and clog the bearings. If neatsfoot oil be not procurable, poppy, sesamum or olive oil may be used, not mustard, castor or cocoa-nut oil.

63. *Estimating wind force.*—At stations unprovided with an anemometer, the force of the wind is to be estimated and recorded in numbers, 1 to 6, as follows:—

Light wind	...	...	No. 1 = 1 lbs. pressure.
Moderate	...	...	„ 2 = 4 lb. „
Fresh	...	...	„ 3 = 9 lbs. „
Strong	...	...	„ 4 = 16 lbs. „
Heavy	...	...	„ 5 = 25 lbs. „
Violent (hurricane)		...	„ 6 = 36 lbs. „

CLOUD AND WEATHER OBSERVATIONS.

64. *Clouds.*—Estimate the proportion of clear, unclouded sky visible in tenths of the entire expanse. An unclouded sky is '0,' one entirely overcast is '10' [§ 99]. Omit from the estimate clouds low down, near the horizon.

65. Notice the kinds of clouds visible [§§ 100—107] and the direction of their motion [§ 110], also, when possible, their rate of movement [§ 110]. If those at different elevations are moving from different quarters, observe both, and write them down thus, indicating the compass point by the figures given in § 83:

$$``\ \frac{\text{C k. from 6.}}{\text{K. from 18.}}\ "$$

66. *Weather symbols, &c.*—Learn the use of the weather initials and symbols, and use them intelligently to describe what is observed. Expressions descriptive of the personal feelings, such as "close," "sultry," "cool," "pleasant," &c., are of no value.

67. These observations should be made in the intervals of the regular hours of reading the instruments, and the hour to which the observation refers is to be noted. The hours of rainfall, of thunder storms, dust storms or hail, &c., are to be noted against the appropriate symbols.

68. The occurrence of dew on the herbage, or fog in the early morning should always be noticed and entered in the register.

REGISTERS.

69. *Registers.*—Two forms are used for registering. The smaller, termed the "observer's" form B, is for writing down the observations as made without reduction or correction. The larger, termed the "record" form A, is for reduced and corrected observations, and the calculated means. For filling these, see §§ 148,149.

70. The observer's form (B) contains columns for 8 days. A new form is to be commenced on the 1st and [illegible] of each month.

71. Be careful to enter the name of the station at the top of each form, and in the first column the distinctive numbers of all the instruments in use.

72. Form A contains the observations of one month. The information required in the headings of the form and in those of the several columns is never to be omitted.

73. Neat and distinct handwriting is indispensable in filling the forms.

TELEGRAMS.

74. *Time of despatch.*—Stations which send daily one telegram only, which contains the report of two sets of observations, should despatch it as soon as possible after 10h.; stations which telegraph twice daily, as soon as possible after 10h. and 16h.

75. *Contents of telegram.*—Each telegram will consist of the date and hour, three groups of figures and their doubles, giving the instrumental readings, and *brief* verbal reports or weather initials, as follow:

The first group consists of the barometer reading *to two places of decimals*, and with the first figure (always 2 or 3) omitted, and the reading of the attached thermometer making five figures in all.

The second group will consist of the reading of the dry-bulb thermometer, omitting decimals (two figures), the difference of it and the wet bulb (one or two figures), and the rainfall since the previous telegraphic report in inches and tenths (two figures), omitting the smaller decimals. If there be no rain, put "00."

The third group will consist of the direction of the wind (always consisting of two figures, with a "0" before the figure if it be less than 10 (=E. S. E.), its velocity in miles per hour (also always two figures, and three figures if the velocity amounts to 10 miles or more), or, in the absence of an anemometer, the estimated force of the wind (one figure), and the direction from which the clouds are moving (two figures). If there be no cloud, these two figures will be cyphers.

76. Remarks are to be telegraphed in the initial letters [§ 112], as far as possible, and are in all cases to be as brief as possible.

77. The following is given as a specimen of a telegram, together with the interpretation:—

Telegram.

716 ...	97688 ...	half ..	195376
	901000 ...	" ...	1802000
	2411800 .	" ...	4823600
		c.	
810 ...	98085 ...	half ...	196170
	87301 ...	" ...	174602
	202616 ...	" ...	405232
		c. v.	

Interpretation.

Date	7th	8th
Hour	16h	10h
Barometer...	29·76	29·08
Attached thermometer... ...	88	85
Thermometer, dry bulb ...	90	87
Difference (wet and dry) ...	10	3
Rainfall	0·0	0·1
Wind direction	W.	S.W.
Wind movement, miles per hour ...	11·8	2·6
Cloud direction	0·0	S.
Weather initials	*c.*	*c.v.*

RULES FOR HOURLY OBSERVATIONS.

1. These are to be recorded on four days in each month, *viz.*, the 7th, 14th, 21st, and 28th.

2. The first set of observations to be taken at midnight of the 6th, 13th, &c., and to be repeated every hour thereafter till midnight of 7th, 14th, &c. Each series will, therefore, consist of 25 sets of observations.

3. All the instruments are to be observed, except that the self-registering maximum thermometers[a] are not to be registered between 16h. and sunrise on the following morning, nor the minimum self-registering thermometers between sunrise and the following sunset.

4. Special forms will be supplied for entering the observations.

5. The superintending officer in charge should allot the hours of observation between the two observers, not leaving the division to their discretion or mutual understanding. The hours from midnight to sunrise, and sunset to midnight, should be divided in such a manner that neither observer shall be on duty for more than 3 hours continuously. Thus, if observer A. begins the series at midnight, he is to call B. at 3h., and the 3h. set will be taken by the two together; B. will then remain on duty till 6h. In like manner, after 18h. one observer will be on duty from 18h. to 21h., and the other from 21h. to midnight.

6. In order that there may be no difficulty in tracing false or erroneous entries home to the observer at fault, each observer is to initial the observations for which he is responsible.

7. If, by accident, a set of observations has been missed, the observer is on no account to attempt to interpolate them. Any attempt to do so will subject the observer to fine or dismissal.

8. All the maximum thermometers, including that for solar radiation,[a] are to be observed with the other instruments from sunrise until they reach their maximum.

9. All minimum thermometers, including that for grass radiation, are to be read every hour as ordinary thermometers between sunset and sunrise.

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[a] At observatories that are supplied with a non-registering solar thermometer, the sun observations are to be recorded hourly from sunrise to sunset.

PART II:

METEOROLOGY OF INDIA.

INTRODUCTION.

IN the first part of this little manual, I have described in detail the methods of making meteorological observations in such a manner that they may furnish a useful basis for scientific enquiry. But it would be an error to suppose that the mere recording of phenomena constitutes science. Observations are simply the materials which are afterwards to be worked up to more or less generalized conclusions: and the former part of this little treatise has for its object, to ensure that the observations shall have a well-defined meaning, to the end that they may afford a firm and sure foundation for the superstructure which is afterwards to be raised upon them.

The object of all science, as it has been justly defined by Herbert Spencer, is to enable us to make *quantitative* predictions of phenomena, —not only to foretell their occurrence in general terms, but to predict their time and exact measure. It is a simple truism to say that in the domain of meteorology very small advances have yet been made to this end. A difficulty, which has greatly retarded its progress in comparison with that of some other branches of natural science, is, that the greater and more important part of the field of work is practically inaccessible to us. We may acquaint ourselves as thoroughly as we please with the changes that are in progress immediately around us, in the lowest stratum of the atmospheric ocean in which we live and breathe: but we know but little and have but slight means of gauging those, perhaps, more influential revolutions of physical condition, which are incessantly in progress at elevations, where the retarding effect of terrestrial friction is practically evanescent; and where, when the earth's surface is screened from the direct action of the solar rays by the dense clouds of the lower and middle atmosphere, that heat, which is the prime source of all

atmospheric energy, is only the more active,—is still doing its work, by evaporating the cloud surface, and lowering the density of the higher strata of air with increased and compensating vigour.

But this is not all. The atmosphere, unlike the ocean, is undivided and uninterrupted; and every change of state, in any part of its expanse, sends forth a pulsation of energy which is speedily felt far and wide. It is rarely indeed that we are in a position to assert that even the more important of those primary effects of solar or terrestrial radiation,—of gain or loss of heat,—whose ulterior consequences we feel in changes of wind, in the gathering storm, in prolonged drought, or deluging rainfall, have their seat in regions of which we have or can gain any knowledge. As yet, systematic observation has been carried out over but a small portion of the earth; and it is only of late years, that any organized endeavour has been made, on a large scale, to bring the results of even this much together; and to exhibit the facts in the form of synoptic charts, which give a bird's eye view of the conditions, prevailing at one and the same time, over a considerable tract of the earth's surface. Till this was done, observers might indeed learn, by year-long observation in limited regions, that certain uniformities were traceable amid the immense vicissitudes of the local climate; but they were for the most part of the nature of empirical laws, the determining causes and explanation of which they had no means of searching out. To Francis Galton[1] is due the first attempt to open out this new and powerful method of research; and the great strides that have been made in recent years, both in America and Europe, in advancing our knowledge of weather changes, is owing in no small measure to the elaborate working out of his idea, aided by the telegraph; the results of which are now seen in the admirable weather charts of General Meyer of the U. S. Signal Service, in those of the London Meteorological Office, in the Paris *Bulletins* and in the atlases of Leverrier and Hoffmeyer.

In Europe and America, the great extension given to work of this kind has been prompted mainly, though not exclusively, by the deeply-felt importance of storm warnings; of affording to shipping and the fishing population of the coasts, some hours' foreknowledge of the impending tempest; and the system of weather telegraphy, and the rapid publication of charts and bulletins, which are essential to this end, have come to be regarded, by the general public, as the most important, as they are the most obvious features of recent activity in the field of meteorological science. This, however, would be an error. There can be no doubt of the great advantage gained in bringing together the observations of a large area around, while the local phenomena are still fresh in the memory; but for

[1] See his *Meteorographica*, 1863.

the purposes of study, the field of view thus brought under command is in most cases limited : and, after all, it is by the leisurely examination and comparison of phenomena, frequently not of those which are the most obvious and striking, that the greatest advances are made in science. The system of weather telegraphy will gain in success and importance, *pari passu* with our knowledge of the laws that regulate the internal movements of the atmosphere; and this is the business immediately before us.

I have said that one great difficulty in our way to the attainment of this object lies in the fact that the field of our operations is in great part inaccessible to us, and very much more but imperfectly accessible. We are in the position of a commander on a vast battle-field who can find no eminence from which he may gain a bird's-eye view of the combat. Could we but find some isolated tract of mountain, plain and ocean, under a wide range of latitude, girdled round by a giant mountain chain that should completely shut in and isolate some millions of square miles of the atmosphere, resting on a surface vast and varied enough to exhibit within itself all those contrasts of desert and forest, of plain, plateau and mountain ridge, of continent and sea, that we meet with on the earth's surface; and could we, by balloons and fixed observatories at different heights, well distributed through such a region, note the loss or gain of heat in each part, hour by hour and day by day, gauge the currents set up within it and the changing composition of the air; and, to use Balfour Stewart's expression, put each section 'under a meteorological blockade', a few years would suffice to place our knowledge of meteorological laws on a very advanced footing; and its further progress would then await little more than the registration of those changes that are secular (such as the effects of the possible variation of the sun's heat); and the improvement of mathematical methods, to enable us to deal with the complicated problems that would present themselves in aero-dynamics.

In India we have the nearest approach to such a region that is to be found probably on the earth's surface. It is a safe prophecy that, given a few earnest and intelligent workers, this country will one day play a part second to none in the advancement of rational meteorology. As England is an epitome of stratigraphic geology, so is India an epitome of atmospheric physics; and, while it presents within itself the most varied conditions of form and surface, and, together with its seas, the great primary contrast of continent and ocean, ranging through nearly 30 degrees of latitude, and during five months of the year, bathed in the intense radiation of a vertical sun, it is, so to speak, a secluded and independent area. On the north, the Himálaya shuts in the lower half of the atmosphere and constitutes the natural limit of

the monsoons; on the south, an only less defined meteorological frontier exists in the zone of all but unvarying barometric pressure of the equatorial belt. For although the monsoons do, at certain seasons of the year, blow across this belt, between Australia on the one hand and India on the other, it is nevertheless a kind of neutral axis, the fulcrum, so to speak, on which the plane of equal pressure turns, inclining alternately to north and south; and the meteorological conditions on its opposite sides bear a very simple relation of reciprocity.

The question now before us is—how shall these advantages be best turned to account? Clearly, observation, carefully and intelligently conducted, is at the basis of all science. But, in order that our observations may be intelligently made, we must have some clear idea of the purposes they are intended to subserve, and it is to be feared that few persons, even of those who have a real liking for the work, at present aim at much more than preserving a record of how much one season is hotter or wetter than another, or of gaining some knowledge of the characteristics of the local climate as it affects health, agriculture, and other immediate conditions of well-being.

In this, the second part of my little treatise, it will be my object therefore to convey some idea of what are the definite aims of meteorological enquiry in India, in relation to meteorology as a science. The knowledge of climate is only the first and immediate outcome of the work. Our business is to go beyond the mere collection of statistics, to ascertain the *why* and *wherefore* of phenomena; it is *physical meteorology*, and not merely *climatology*.

To begin with, we must start with a clear comprehension of a few established physical laws, which are all important in their bearing on meteorological phenomena. They are not very numerous, nor especially difficult of comprehension, but they must be familiar as grooves of thought to any one who would seek to enter profitably on the field before us. In the second place, I shall describe, as concisely as is compatible with clearness, what is known of the meteorology of India; referring the reader to original sources of information, in case he should desire to gain a further and more especial acquaintance with the facts; and lastly I shall point out certain provinces of investigation, only a few perhaps of a multitude that will present themselves to the mind of any expert, to which, according to his opportunities, the attention of the reader may be profitably turned.

The knowledge of certain departments of Indian Zoology has been popularized, and a host of ardent collectors and observers has been created by the publication of Dr. Jerdon's admirable manuals of the mammals and birds of India. The Manual of the Geology of India,

which is now in preparation by the most accomplished officers of the Geological Survey, will doubtless, in like manner, serve to bring forward many who will render effectual assistance in working out the details of the local geology. And I entertain a hope that the not less rich and engaging field of Indian meteorology may also be entered upon by some able volunteers, if I should succeed in attracting their interest, by presenting to them a picture, however imperfect, of the beautiful scheme of action and interaction of which our Indian atmosphere is the theatre.

PHYSICAL PROPERTIES OF AIR AND VAPOUR.

1. **Air and vapour.**—That atmospheric air consists essentially of a mixture of permanent gases (chiefly oxygen and nitrogen), with which is intermingled a small and variable proportion of water vapour, is a fact familiar to every tyro in physical science. In the very different behaviour of the permanent gases on the one hand and the water vapour on the other, when subjected to great variations of heat and pressure, lies the first important class of phenomena which it concerns us to familiarize to our minds. We will, in the first place, consider the effects of these agents on the elastic pressure of the dry air and vapour.

2. **Weight and pressure.**—Both air and vapour, being elastic fluids, exert an elastic pressure which is independent of their weight, and must be clearly distinguished from it. Weight they have indeed, in common with all other forms of matter; and this, in the case of the atmosphere, is such that (whatever its composition), if, *when perfectly quiescent*, it causes the barometric column ([1] reduced to 32° Fahrenheit) to stand at 30 inches, each vertical column, one square inch in section, and of the full height of the atmosphere above the level of the barometer cistern, has a weight of 14·735 lbs. avoirdupois. This is also the weight of a column of mercury at 32° Fahrenheit, 30 inches high and 1 square inch in section. But we learn from mechanics that, if the air is in motion either upwards or downwards, either expanding or contracting, the height of the barometric column, though always a measure of the *pressure* of the air acting on it, is no longer an exact measure of its *weight*. The weight of one cubic foot of dry air, under a barometric pressure of 30 inches and at 32° Fahrenheit, is 565 grains.

From these data it follows that, if the atmosphere were throughout of uniform density and of the temperature of the freezing point, its height would be 26,288 feet. For 14·735 lbs., the weight of a column one square inch in section, are 103,145 grains; and therefore a column of one square foot in section would weigh 103,145 × 144 = 14,852,880 grains; which, divided by 565, = 26,288. This is called the height of a *homogeneous atmosphere*; and, in order to allow for the diminution of gravity at great heights, it is usually taken in round figures as 26,250 feet. It is an important datum in many physical calculations, and it will be designated by the symbol H. Its value is, however, independent of the pressure, for, as will be seen in the next paragraph, the density of

[1] Part I, § 14.

air, and therefore the weight of a column of given dimensions, varies directly as its pressure, *so long as the temperature is unaltered:* and therefore, whatever may be the pressure of the air, provided its temperature is that of the freezing point, it presses with the same force as a homogeneous atmosphere *of the same pressure,* of height H; the force of gravity being assumed constant. The correction for variations of temperature will be given further on.

3. Boyle's law.—A given mass of dry air, like all permanent gases and mixtures of permanent gases, exerts an elastic pressure inversely proportional to the volume it occupies; so that, if it be compressed into half its original volume, its pressure is doubled; and reciprocally, if the external pressure upon it be doubled, its elastic pressure will adjust itself to the compressing force, and it will then occupy half its previous volume. This important law was originally established by Boyle, and is known as *Boyle's law.* Since, moreover, the density of one and the same gas at constant temperature, is inversely as its volume, its pressure varies directly as its density. This law is simply expressed by the following formula, wherein V, P and ρ express a standard volume (say one cubic foot), a standard pressure (30 inches), and the density of a gas at that pressure; and V_p, P, and ρ_p any other correlated volume, pressure and density of the same gas:—

$$\frac{V_p}{V} = \frac{P}{P} = \frac{\rho}{\rho_p} \qquad (1)$$

Boyle's law is limited by the condition that the gas shall be of the same temperature throughout these changes of volume; but it holds good for dry air (with near approximation) through the full range of pressure as yet experimentally tried. This, we shall see, is not the case with vapour.

4. Vertical distribution of pressure.—An important consequence of Boyle's law, combined with that next to be noticed, and the natural distribution of temperature, is the rate (well known from observations with the barometer) at which the pressure of the atmosphere, and therefore (disregarding the small changes arising from its movements) its density, decrease as we ascend above the level of the sea. At about 18,000 feet, the pressure is only half of that at sea-level; which indicates that one-half the ponderable mass of the atmosphere is below 18,000 feet; although, from the phenomena of twilight, it follows that the whole height of the atmosphere cannot be less than 40 miles; and those of luminous meteors prove the existence of a resisting medium up to 200 miles.

The law of decreasing pressure will be found explained in *Herschel's Meteorology, Ganot's Physics, Maxwell's Theory of Heat, Deschanel's Natural Philosophy*, and other manuals of physics. In its simplest form, applying to the case of an atmosphere of uniform temperature and composition, and on the (untrue) assumption that the force of gravity is the same at all heights, it would stand thus:—If H is any given height and P' the pressure at height H, and if H is the height of a homogeneous atmosphere the pressure of which on its base is P

$$\log.\frac{P'}{P} = -A\,\frac{H}{\mathsf{H}}$$

whence $\log. P' = \log. P - A\,\frac{H}{\mathsf{H}}$

A is a value which depends on the density of the air and the force of gravity, and expresses the ratio of the weights of equal volumes of air and mercury, if the pressures are expressed in barometric measure. Moreover, if the logarithms used are the ordinary Briggs's logarithms to base 10, it includes as one of its factors the modulus of that system. The different values of $\frac{A}{\mathsf{H}}$ (or their logarithms) corresponding to different temperatures, are given in numerous tables, of which that published at Roorkee by Captain Allan Cunningham, R.E., may be recommended for use in India.

5. Charles' law.—The law according to which the pressure of a confined mass of air varies with changes of temperature was first ascertained by Charles,[1] and has been subjected to a very rigorous verification by Regnault. Generally stated, it is that the pressure of a gas, kept at constant volume, increases by equal increments for equal increments of temperature. In the case of dry air, Regnault has determined the amount of this increment to be ·002036 of that which it has at the freezing point, for each degree Fahrenheit between 32° and 212.° This is called the *mean co-efficient of elasticity*, and is represented by the symbol α. If the air be unconfined,—that is, if it be free to expand under a constant pressure,—then its volume increases ·002039 of that which it has at the freezing point, for each degree Fahrenheit between the same temperatures. This is called the *mean co-efficient of dilatation*. Charles' law is not rigorously true, but for all ordinary meteorological problems, we may assume its exactitude without appreciable error.

In meteorological calculations we may generally assume these two co-efficients as equal; in which case, the law of pressure and volume, in

[1] It is frequently, but improperly, termed Gay Lussac's law, since Charles preceded him in its discovery. Still less properly, it is occasionally referred to as Dalton's law.

respect of temperature, may be represented by the following formula, wherein V_0 and P_0 represent the volume and pressure of a gas at 32° Fahrenheit, and V_t and P_t the volume and pressure at temperature t on the Fahrenheit scale, one being supposed constant while the other varies.

$$\frac{V}{V_0}=\frac{P_t}{P_0}=\frac{1+\alpha\,(t-32)}{1} \qquad (2)$$

6. Vertical distribution of pressure modified by temperature.—The fact, then, that the density of one and the same gas varies with the temperature while its pressure remains constant, taken in conjunction with that yielded by observation, *viz.*, that the temperature of the atmosphere is different at different heights, shews that the temperature correction of the factor H of the barometric formula has different values in different parts of one and the same column. In the practical application of the formula, an approximation is made by assuming a mean temperature throughout; and to ascertain this, since it can rarely be observed at more than one or two points, it is usual either to assume a mean law of the distribution of temperature, or to observe the temperature at the top and bottom of a column of air, and, if possible, at one or more intermediate points, and to take the mean of these observations. In either case, however, the assumption is subject to a considerable range of error, and hence one reason for the uncertainty of heights which are computed with such observations. [See Part I, § 16.]

7. Absolute temperature.—There is a method of representing the law of expansion which is very convenient in practice. It depends on the discovery of Sir Wm. Thomson, that a body cooled to 461·2° below the zero of the Fahrenheit thermometer would be absolutely deprived of heat. Temperatures reckoned from this point, the absolute zero, are termed *absolute temperatures*; and thus the freezing point on the Fahrenheit scale (32°) becomes 493·2° in Fahrenheit degrees on the absolute scale. Now the coefficient of expansion of air, ·002039, is almost exactly $\frac{1}{490}$ in vulgar fractions; so that the volume of a gas at the freezing point is 490 times the increment of expansion for 1°. Disregarding the difference between 490 and 493·2, then, we may assert that the volume of air at constant pressure is directly as its absolute temperature; and, with somewhat nearer approximation, that at constant volume, its pressure is also as its absolute temperature, the absolute temperature being the Fahrenheit temperature + 461·2°. Calling T_0 the absolute temperature of the freezing point, and T any other absolute temperature on the same scale, Charles' law may be represented by—

$$\frac{V_t}{V_0}=\frac{P_t}{P_0}=\frac{T}{T_0} \qquad (3)$$

8. Densities of air and vapour.—The density of water vapour is 0·623 of that of air, when both are at the same temperature and pressure. Therefore, the weights of equal volumes of dry air and vapour, at the same temperature and pressure, are as 1 : 0·623; and in a mixture of air and vapour, the vapour weighs 0·623 times only as much as the dry air which would replace it, in order to maintain the pressure unaltered. This proportion is almost exactly the same as $\frac{5}{8}$.

9. Physical properties of vapour.—The pressure of water vapour conforms approximately to Boyle's and Charles' laws when not in contact with its own liquid, and up to certain limits which depend on the temperature. For every temperature there is a certain maximum tension or elastic pressure, which cannot be exceeded. If a higher pressure than this be brought to bear on the vapour, the vapour will not be compressed till its tension is in equilibrium with the external pressure, as would be the case with air; but it will be condensed as fast as its volume is reduced, the tension all the time remaining constant. Conversely, there is a minimum temperature corresponding to every pressure, and if vapour be cooled down under a constant pressure, as soon as that temperature is reached, it will begin to condense. This temperature is called the *temperature of saturation* for that pressure. Table III in the collection of tables, that accompany this work, gives the vapour tension or pressure corresponding to saturation, at each temperature up to 95°, as determined by Regnault, or rather as computed from Regnault's tables.

It will be observed that the tension of saturation rises much more rapidly than the corresponding temperature. The law according to which it increases is not yet exactly known; but for temperatures between the freezing and boiling points of water, Regnault used a formula of interpolation,[1] in which the pressure e is an exponential function of the temperature, and which is as follows :—

$$\log. e = a + b\,\alpha^{t} + c\,\beta^{t}$$

the values of the several constants a, b, c, α, β, being obtained from five sets of observations at the temperatures 0°, 25°, 50°, 75° and 100° Cent.

Magnus had previously employed another formula, which, although somewhat less exact, has certain advantages in calculation; and we shall use it in treating of the dynamic cooling of saturated air in the latter part of this chapter § 38. It is as follows :—

$$e = 4{\cdot}525 \times 10^{\frac{a\,t}{b\,+\,t}}$$

[1] *Comptes Rendus* for April 1845.

The values of a and b for temperatures on the Fahrenheit scale, reckoned from the freezing point (substituting $t-32$ for t), are—

$$a = 7{\cdot}4475$$
$$b = 422{\cdot}45$$

Vapour in contact with its own liquid must always be saturated, but this saturation will not necessarily extend far from the surface of the liquid, if the vapour be mingled with air, which retards its movement, § 12.

10. Saturation and relative humidity.—These properties of water vapour are of the very highest importance in meteorology. They furnish the explanation of evaporation, the formation of fogs, cloud and rain, the variation of the relative humidity of the air with changes of temperature, and a multitude of other phenomena. Some of these may be here noticed. Others must be reserved until we have discussed some other laws of heat which are equally concerned in their production.

The stratum of air that rests immediately on the ocean or other water expanse will always be very near saturation. For, whatever be the temperature, the tension of the vapour in that stratum will speedily adjust itself to saturation at that temperature, either by the production of additional vapour from the water surface, or by the condensation of the excess, if the temperature falls. Hence, at sea, the humidity of the air is always high or near saturation, and the wet bulb thermometer, on board a ship a few feet only above the sea surface, rarely falls more than 1° or 2° below the dry bulb.

That a mass of air which is hygrometrically dry may yet hold more vapour than another mass of air with a higher relative humidity, depends on the fact that, as the temperature rises, the tension of saturation corresponding to the temperature rises much more rapidly. Thus, air containing vapour at a tension of 0·248 will be saturated at 40°; but if its temperature be 86°, at which the tension of saturation is 1·245 inches, the relative humidity will be only 20 per cent.

11. Formation of cloud, fog and rain.—The formation of cloud and rain are determined by the cooling of air charged with vapour. This cooling may arise from various causes; from radiation, from loss of heat by ascending (dynamic cooling, § 27), by contact with cold surfaces, such as the forest or snow-clad slopes of mountains, or by intermixture with air at a lower temperature. Cloud and fog are formed as soon as the cooling has brought the temperature of the air and its contained vapour below the temperature of saturation.

The formation of cloud by the intermixture of warm and cold air, both of which may be a little below saturation, is explained by the fol

lowing considerations. If two equal masses of dry air at different temperatures be mixed, the resulting temperature will be the mean of the two. But the tension of saturation at this mean temperature is always below the mean of the tensions at the original temperatures. If equal weights of air at 90° and air at 60° be mixed, the resulting temperature will be 75°. Now, the tension of saturation at 90° is 1·413, that at 60° 0 519, and the mean of the two therefore 0·966. But the tension of saturation at 75° is 0·870; and therefore, vapour exercising a pressure of 0·096 must be condensed, to reduce the tension to saturation at 75°.

In point of fact, however, unless heat be allowed to escape during the process, the temperature resulting from the intermixture of two equal masses of saturated air at different temperatures, will be somewhat higher than their mean, owing to the emission of latent heat from the condensed vapour, § 19.

12. **Diffusion.—Dalton's law.**—The elastic pressure of a mixture of air and vapour is the sum of the individual pressures of the constituents. It was a discovery of Dalton's that a space filled with any gas or vapour is as a vacuum to any other gas or vapour; and hence, in dry air, or moist air below saturation, evaporation will go on from a fluid surface and the vapour will diffuse through the air, until each cubic foot contains as much vapour as it would do were no air present. This, however, is practically true only of confined air. To the tension of the dry air is added that of the vapour which diffuses into it; and, in the free atmosphere, if the superincumbent pressure is constant, the additional pressure will speedily be reduced by the expansion of the saturescent mass. Diffusion is by no means instantaneous; on the contrary, it occupies a very considerable time, in consequence of the internal friction of the mass. the collision of the molecules of the diffusing gas with those into which it diffuses; and its rate varies inversely as the total pressure, and as the square root of the product of the densities, and directly as the absolute temperature of the gases.

According to a calculation of Prof. Stephan's, based on Prof. Loschmidt's experiments, in a tube one metre in length, the lower half of which was originally filled with damp air, and the upper half with dry air, both at the freezing point, the pressure of the vapour p_t that has reached the upper end of the tube after t hours' diffusion, bears the following ratio y to the original pressure p of the vapour in the lower half:—

$t =$	$\frac{1}{2}$	1	$\frac{3}{2}$	2
$y = \frac{p_t}{p} =$	0·08	0·22	0·31	0·38

13. Atmosphere of vapour.—As a consequence of Dalton's law, the tendency of the vapour in the atmosphere is to diffuse upwards, and to arrange itself independently of the air and as if no air were present, in strata of successively decreasing density and pressure, according to the law already given in the case of dry air. That is to say, until the tension of the vapour shall diminish in a geometrical ratio as the height increases in an arithmetical ratio, and the law of pressure at any given elevation shall be given by the formula;—

$$\log. p' = \log. p - A\frac{H}{H'},$$

where H′ represents the height of a homogeneous atmosphere of vapour exercising pressure p on its base. But, since the density of vapour is only $\frac{5}{8}$ths that of air, H′ will be $\frac{8}{5}$ths as high as a homogeneous atmosphere of air that would have the same pressure p on its base, and the height, therefore, at which p' would be half of p, would be actually about $\frac{8}{5}\times 18{,}000$ feet=28,800 feet; were not the temperature prevailing at that elevation, in general, far lower than that of saturation under the supposed conditions. The consequence of the actual distribution of temperature is, that vapour is always tending to ascend through the atmosphere,—tending towards a distribution which it can never attain,—because such distribution is inconsistent with the existing distribution of temperature; for the vapour condenses and becomes cloud long before it can reach the requisite elevation.

The above considerations explain the fact that, as a general rule, over the land, the air becomes relatively more humid as we ascend, and that clouds often exist at a moderate height when the air at the ground surface is very considerably below saturation. The further fact that at hill stations in the Himalaya, even during fine dry weather, the relative humidity of the air is always much higher than on the plains below, is explained in like manner.

14. Erroneous application of Dalton's law.—Until within the last few years, it was a common custom, in reducing the observations of barometric-pressure, to deduct from the total pressure the tension of the water vapour in the air, and to call the residue the pressure of dry air, on the implied assumption that the atmospheres of vapour and dry air are practically distinct. General Strachey, however, proved by a course of reasoning similar to that above given, that such a distribution of vapour is inconsistent with the observed vertical decrease of temperature, and it is, moreover, inconsistent with the observations made during balloon ascents. M. Lamont of Munich further demonstrated by an ingenious laboratory experiment, described in Professor Balfour Stewart's

Treatise on Heat, that vapour, by its friction, communicates its pressure to the dry air with which it is intermingled; and hence, although the separation of the pressures may indicate the proportions in which air and vapour contribute to the total pressure around the cistern of the barometer, the distinction has only a local meaning, and does not apply to the great mass of the superincumbent atmosphere.

The failure to recognize this fact has led to some erroneous reasoning, traces of which may still be found in some of our hand-books.

15. Diurnal variation of vapour tension.—An important class of facts, which is partially explained by the vertical diffusion of vapour, is the variation of the tension of vapour during the day. At sea, and generally in damp countries such as England, and in Bengal near the sea coast during the rains, the tension of the aqueous vapour in the air rises as the temperature rises, although much less rapidly, and attains its maximum about the warmest time of day. In dry countries, on the other hand, such as the interior of India in the spring months, the vapour tension rises only for the first hour or two after sunrise. After this it falls, despite the rapidly increasing temperature, and is lowest when the temperature is highest. As the temperature falls in the evening; the vapour tension rises, and reaches its maximum an hour or two after sunset.

This probably depends on the ratio between the rate of production of vapour on the one hand, and its rate of removal on the other; the rate of diffusion varies as the square of the absolute temperature, and therefore by diffusion alone the removal of vapour will be accelerated, at least in that proportion, as the temperature rises; while from a dry land surface, with little vegetation, the production of vapour may not increase even directly as the temperature; nay, may even fall after the more superficial moisture has been dissipated. The subject of the variations of vapour tension in the atmosphere at different heights is one that much requires investigation.

16. Diurnal variation of cloud and rainfall.—That the humidity of the cloud-forming strata of the atmosphère, and in all probability the tension at vapour at comparatively moderate heights, do not follow the same law of diurnal variation as in that stratum which rests immediately on the earth's surface, may be inferred conclusively from the observed diurnal variation of the cloud proportion and of the frequency of rainfall. An examination of several years' registers of several stations in Bengal shews, that the hour when the sky is most free from clouds, when therefore, at the elevations at which clouds ordinarily form, the humidity is on an average lower than at any

other time of day, is about 10 P.M.; while, near the earth's surface, the lowest humidity is coincident with the highest temperature or between 2 and 4 P.M. This occurrence of the cloud minimum some hours after sunset seems to be a general, and not merely a local law, since Kreil, speaking of Europe, mentions it as a well-known phenomenon. Moreover, Dr. Neumayer, in his discussion of the 5 years' observations at the Flag-staff observatory, Melbourne, has shewn that, at that station, in every month of the year, except November, the time of minimum cloud falls between half-past 8 P.M. and half-past 1 A.M., and that, on the mean of the year, it occurs at half-past 9 P.M. This is only three hours later than the average maximum vapour tension at the same place at the earth's surface.

The phenomena of rainfall afford similar evidence. It appears from the summarized results of the rainfall of Calcutta, that the hour at which rainfall is least frequent is about midnight or shortly after, and that it is most frequent from 1 to 3 P.M.; that is, when, in the hot season, the vapour tension and humidity are lowest at the ground surface.

17. Heat unit.—Hitherto, we have attended only to those variations in the physical condition of air and vapour that accompany changes of pressure and temperature. We must now turn to the *quantitative* relations between heat and these two principal constituents of the atmosphere, and the phenomena that accompany the absorption and emission of given measured quantities of heat; adopting, as the unit measure of heat, that quantity which will raise 1℔ of pure water from 32° to 33° Fahrenheit. This quantity is called a *heat unit.*

18. Specific heats of air and vapour.—If this quantity of heat be absorbed by 1℔ of air, or by the same weight of water vapour, free to expand under a constant pressure, instead of being heated only 1° Fahr., the former will be heated 4·21°, the latter 2·08°; and conversely, the quantities of heat required to raise the same weight of air and water-vapour 1° of temperature, when at constant pressure, are in the former case 0·2375, in the latter 0·4805 of a heat unit. These latter quantities are termed the *specific heats* of air and vapour *at constant pressure;* water, as above specified, being taken as the standard, whose specific heat=1. The specific heat of water and other substances varies to a small extent at different temperatures; but, for gases, the change is very small, and for such ranges as we have to deal with in meteorology, we may assume the specific heat as constant for the same substance in the same physical state. For reasons that will be explained further on (§ 29) the specific heat of air that is not allowed to expand, but is kept at constant volume, as for instance in a closed vessel, is less than

that which is kept at constant pressure and is allowed to expand, *viz.*, ·168· We may distinguish this by the symbol c, and the specific heat at constant pressure by c_p. For the explanation of this difference see §§ 27, 29.

The fact herein illustrated, that different kinds of matter require different quantities of heat to raise equal weights of them through the same range of temperature, is one of high importance in meteorology. The specific heat of the materials forming the land surface may be taken on an average as from $\frac{1}{5}$th to $\frac{1}{4}$th of that of water; and, in consequence, the temperature of the land will rise four or five times as rapidly as that of water for the same quantity of heat absorbed. This is one (but only one) of the reasons why sea winds are cooler than land winds during the hotter part of the year. That the specific heats of air and vapour are respectively less than one-fourth and one-half of that of water, in the same way, partly explains why the atmosphere resting on a water surface is during the day-time somewhat warmer than the surface itself, whereas that which rests on a heated land surface is somewhat cooler than the ground on which it rests. Other facts bearing on this difference of behaviour will be noticed in §§ 19, 22, 24.

19. Latent heat of vapour. Evaporation.—But a far more important cause of the difference in the rate at which water and land surfaces are heated, when both are exposed to the same intensity of the solar radiation, is that, whereas the whole of the absorbed heat goes simply to raise the temperature of dry earth or rock,—of that which is absorbed by water, by far the greater part is used up in the production of vapour, the temperature of which is no higher than that of the water surface from which it proceeds, or that of the air into which it subsequently diffuses. Now, water in the act of passing into vapour, at any temperature, absorbs a large quantity of heat, which is used up simply in transforming water from the liquid into the gaseous condition, and which is again given out when the vapour is condensed and reconverted into water. This quantity varies with the temperature at which the evaporation takes place; and is the greater, the lower the temperature. Regnault, to whose exact experiments we owe so much of our present accurate knowledge of the laws of heat and pneumatics, has determined the law of the *latent heat* of water vapour to be that expressed by the following formula. Let Q = the total quantity of heat required to raise water from 32° Fahrenheit, and to evaporate it at any temperature t; then—

$$Q = 1091{\cdot}7 + {\cdot}305\ (t - 32)\ \text{units of heat} \qquad (4)$$

Q is termed by Regnault, the *total heat* of vapour.

If, then, λ represent the latent heat of vapour at temperature t, since $(t—32)$ units of heat are required to raise the water from 32° to t and—

$$Q = \lambda + (t - 32)$$
$$\lambda = Q - (t - 32)$$
$$= 1091 \cdot 7 - \cdot 695\ (t - 32) \qquad (5)$$

It is, then, the absorption and rendering latent of this large amount of heat in the evaporation of water, that mainly contributes to render the temperature of sea-air so uniform; since, of all that which is absorbed by the water, a very small part is consumed in raising its temperature. The chief condition, that limits the rapidity of evaporation, is the retardation which the vapour experiences in diffusing through an atmosphere already almost at saturation. Other familiar illustrations of the cooling produced by evaporation are,—the action of the wet bulb thermometer,—of tatties and thermantidotes,—of the common mode of cooling water by exposing it in a porous bottle or jar to a hot (and dry) wind,—and in the action of Regnault's and Daniell's hygrometers, in which the cold is produced by the accelerated evaporation of ether; which has, indeed, only one-sixth of the latent heat of steam, but the higher elasticity of the vapour of which facilitates its rapid evaporation.

One further illustration may be mentioned, of which instances may be found in any register of temperature kept during those hot months, in which thunder-storms occasionally occur. On looking through such a register, it will always be found that, on the day after heavy rain, sometimes indeed for two or more days, the temperature is lower than before, and it takes two or three days to recover its former intensity. This is, in great part, owing to the absorption of the heat in evaporating the fallen rain.

20. **Effects of condensation**.—When vapour is condensed, a quantity of heat, exactly equal to that absorbed in its evaporation at the same temperature, is given out. The temperature of those strata of the atmosphere in which cloud is most prevalent is much affected by this action. *But it would be a mistake to suppose that the temperature of any mass of air in the atmosphere is actually raised by the condensation of a part of its moisture.* Condensation can take place only in virtue of either cooling or an increase of the external pressure; and in the open atmosphere, the former is, practically, the only cause operative. It would therefore be a contradiction of effects to suppose that the formation of cloud and rain can actually raise the temperature of the air by emitting latent heat. The effect of this emission is *to retard the fall*

of temperature, and of this action we shall afterwards have to notice one important consequence, *viz.,* its effect on the production of convection currents; as exhibited, for instance, in the formation of cumulus cloud, and the generation of storms of the nor'-wester class; and generally as an important condition in the production of convection currents and winds. Indeed, it may be said that it is the most important cause of the south-west monsoon.

21. Latent heat of liquefaction.—When ice or snow melts, a certain quantity of heat is used up and disappears in effecting the change of condition. This is called the *latent heat of liquefaction.* Each pound of ice at 32° in passing into water at 32° Fahr. absorbs 142·6 units of heat. As in the case of the latent heat of vaporization, it varies with the temperature of liquefaction; but in the conditions met with in nature, this temperature is practically constant, and therefore the latent heat of liquefaction may also be regarded as constant. In treating of the meteorology of India, we shall have but little occasion to refer to this subject, but it has some applications of importance. The chief of these is the influence of the snows of the Himálayas on the temperature of the mountain atmosphere.

22. Comparative effects of heat on pressure.—The contrasted effects of heat on pressure, when employed in the one case in heating air, and in the other in charging it with vapour, are of very high importance, and the formulæ given in the foregoing part of this chapter enable us to compute what effect is produced in the two cases. For, let a given fixed quantity of heat, τ units, be absorbed by a given volume V of dry air at pressure P and absolute temperature T, raising its pressure to $P + p$ and its temperature to $T + \theta$, then by (3) since V is supposed constant—

$$P + p = P\left(1 + \frac{\theta}{T}\right) \text{ and } p = P\frac{\theta}{T} \qquad (6)$$

and since, by (1) and (3), putting P for the standard pressure, the mass of the air heated is $V\rho\,\frac{P\,T_0}{\mathrm{P}\,T}$; if we designate by c the specific heat of the unit mass of air at constant volume—

$$\tau = V\rho\;\theta c\,\frac{P}{\mathrm{P}}\,\frac{T_0}{T} \qquad (7)$$

Now, if the same quantity τ of heat be employed in evaporating water at absolute temperature T' and charging the same volume V of dry air with this vapour, the resulting pressure will, by § 12, be the sum of the

two pressures of the air and vapour. Let this be represented by $P + p'$. Then, since the mass of the vapour added will be $V\sigma \frac{p'}{\mathrm{P}} \frac{T_0}{T}$, when σ is the density of water vapour at P and T_0; putting λ for the latent heat at temperature T—

$$\tau = V\sigma \frac{\lambda p'}{\mathrm{P}} \frac{T_0}{T}$$

But, by § 8, $\sigma = \frac{5}{8} \rho$ approximately. Therefore we may put—

$$\tau = V \tfrac{5}{8} \rho \lambda \frac{p'}{\mathrm{P}} \frac{T_0}{T} \qquad (8)$$

and equating the two values of τ in (7) and (8)—

$$V \rho \theta c \frac{P}{\mathrm{P}} \frac{T_0}{T} = V \tfrac{5}{8} \rho \lambda \frac{p'}{\mathrm{P}} \frac{T_0}{T}$$

and eliminating the common factors—

$$P \theta c = \tfrac{5}{8} p' \lambda$$

$$p' = P \tfrac{8}{5} \frac{\theta c}{\lambda} \qquad (9)$$

From (6) and (9) eliminating P and θ—

$$\frac{p}{p'} = \tfrac{5}{8} \frac{\lambda}{cT} \qquad (10)$$

For the value of $t - 32$ in (5) we may put its equivalent on the absolute scale $(T - T_0')$; and substituting for λ this alternative value in equation (10), and for c and T_0 their constant numerical equivalents 0·168 and 493·2 from §§ 7, 18,—

$$\frac{p}{p'} = \tfrac{5}{8} \frac{1091{\cdot}7 - {\cdot}695\ (T - 493{\cdot}2)}{0{\cdot}168 T}$$

$$= \frac{5336{\cdot}6}{T} - 2{\cdot}58.$$

If we now substitute for T any probable temperature, for instance, 541·2 = 80° on the Fahrenheit scale, it results that the increment of pressure is 7·27, or more than seven times as great in the case of the heating of dry air, as in that of evaporation; and the ratio is the greater the lower the temperature.

While, however, the immediate effect of heat is much greater in the case of dry air than in that of evaporation, the latter is more durable. Sensible heat is readily dissipated by radiation; but that which has become latent, or, in stricter language, has been used up in producing a molecular change, cannot be emitted, until, by the reversal of that molecular change, it once more appears as heat.

In working out the above problem, we have supposed the volume to be constant, for the sake of simplifying the calculation. But, to apply

the result to the case of the atmosphere, we must correct it for the case of expansion under a constant pressure. This we shall do when we have discussed the laws of the dynamic heating and cooling of air, § 29.

23. Radiation.—If a ray of solar light and heat (in general terms, *radiation*) from a narrow slit in an opaque screen, be passed through a glass prism at a proper angle, it is bent out of its direct path, and spread out as a coloured band called the *spectrum*, which is violet at the end most bent from the original direction, and red at that which is least so. Red light is, therefore, light of *low refraction*. If a band of this spectrum fall on a narrow thermopile, coated with lamp black, its longer axis being parallel with that of the prism and connected with a very sensitive galvanometer, a divergence of the galvanometer needle will shew that the rays of coloured light can warm any body on which they fall and which absorbs them. But this heating effect is extremely weak in the violet and blue rays, increases rapidly as the thermopile is moved towards the red end of the spectrum, and is greatest when it has passed quite beyond the red, and is exposed to an invisible radiation, which is of still lower refraction than the red rays. These are termed the *dark heat rays*. A beam of radiation from an electric lamp close at hand affords dark heat rays far more intense, relatively to the coloured rays, and of greater extent, than a beam of solar radiation which has traversed the whole thickness of the earth's atmosphere; especially if the prism used be made of pure rock salt instead of glass. . The reason of this is, that dark heat rays are, to a great extent, absorbed by the atmosphere, which the light rays traverse freely, and such is also the case with glass. Rock salt, on the other hand, allows dark heat to traverse it with comparatively but slight absorption. Such substances are called *diathermanous;* while those which, like alum, although they may be transparent to luminous, are opaque to dark heat, are said to be *athermanous*. The heat which is given out by bodies below the temperature of incandescence is all dark heat.

24. Diathermancy of air and vapour.—Although both air and vapour are highly[1] transparent to light, it appeared from the results

[1] Not indeed *absolutely* transparent, more especially water vapour. Certain dark lines and bands in the solar spectrum are due to the absorption of particular rays by the atmosphere, and Forbes and Janssen have observed that water vapour, when in great thickness, exercises a very appreciable and general absorption of the blue and more refrangible rays of the spectrum, and of certain bands in the red; while the greater part of the red and orange rays are freely transmitted. Hence, the brilliant red and orange tints of the clouds at sunset, at which time the solar rays traverse a great thickness of the lower atmosphere, highly charged with vapour.

of Tyndall's experiments,[1] that in their behaviour, when exposed to dark radiation, there is a wide difference between dry air and vapour. According to these results, it appeared that when dark heat, such as that given out from the blackened sides of a vessel containing boiling water, is transmitted through air containing vapour, seventy times as much heat is stopped and absorbed by the invisible water vapour as by the dry air through which it is diffused. The importance of this discovery in its meteorological bearings, if true, would be very great indeed, for, as Tyndall pointed out, it would follow that, of the heat given out from the earth's surface, at least 10 per cent. must be absorbed within 10 feet of the surface. Until quite lately, these conclusions of Tyndall's have been accepted almost unchallenged by the majority of meteorologists and physicists, although the late Professor Magnus of Berlin had failed to verify them; but considerable doubt has lately been thrown upon the conclusiveness of Tyndall's experiments, by M. Hoorweg,[2] who, in repeating that which appeared to be Tyndall's most crucial experiment, has found that the adoption of one additional precaution has, in a great measure, subverted the result obtained by the latter physicist.

The absorption attributed by Tyndall to vapour appears to be really due to a film of water, which condenses on the apparatus, as was pointed out by Magnus; and that of water in the state of vapour is but little greater than that of dry air.

Still later, M. Buff of Giessen[3] has confirmed this result of Hoorweg's, with apparatus of a very different construction. And not only has he demonstrated that air and vapour differ but little in their absorptive power, but he has also shewn that dry air, instead of being, as both Tyndall and Magnus had concluded, nearly as diathermanous as hydrogen, or as empty space, has a high absorption, greater even than that of olefiant gas.[4] The conclusions drawn by Professor Tyndall from the results of his own experiments and which have been largely quoted and appealed to in meteorological works in explanation of atmospheric phenomena, appear therefore to be erroneous.

It is probable that much of that atmospheric absorption, hitherto attributed to vapour, is susceptible of the same explanation as the results of Tyndall's experiments above alluded to. This is, that the radiation

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1 See 'Heat a Mode of Motion,' page 374 *et seq.*

2 Poggendorf's Annalen, CLV, 1875, page 385. As far as I am aware, Dr. Tyndall has not published anything on the subject since the appearance of M. Hoorweg's paper.

3 Pogg. Ann., volume CLVIII, page 177.

4 As the result of his experiments, it absorbed 50 or 60 per cent. of the heat radiated from a polished metal surface at the temperature of boiling water.

is absorbed, not by true vapour, but by some form of condensed vapour, such as cloud in an extremely attenuated condition. The evidence in favour of this view will be adduced in the next following paragraph.

25. Absorption by the atmosphere.—This is a subject which has received considerable attention from physicists, and is one of the highest importance to meteorology. But, as yet, our knowledge of it is very imperfect, and the subversion of the hitherto popular doctrine of the relative athermancy of water vapour to air, which has played so conspicuous a part in most of the recent writings on this branch of meteorology, obliges us to fall back on the individual observations of Forbes, Janssen, Neumayer and others, who have investigated this question of atmospheric absorption by observations on the atmosphere in the mass.

These observations are of two kinds, *viz.*, those which have aimed at a differential measurement of the solar radiation before and after it has been sifted and partially absorbed by different thicknesses of the atmosphere, and those which have compared the cooling of the lowest stratum of air and of the earth on which it rests, in different states of the atmosphere, on the assumption that, under a cloudless sky, the cooling will proceed the faster, the more diathermanous the superincumbent air mass.

Of the former class, perhaps the most valuable and most direct in the information they afford, are the actinometric observations made simultaneously on mountains and on the plains at their foot. Principal Forbes and Kaemtz[1] on the Faulhorn and at Brienz, the Reverend G. C. Hodgkinson and friends[2] on Mount Blanc and at Chamounix, and Dr. Henessy and Mr. Cole[3] at Masuri and Dehra, have recorded observations on this system; the first with Herschell's actinometer, the two latter parties with the actinometer invented by Mr. Hodgkinson and described in the first part of this work, § 55.

Principal Forbes found that, on the 25th September, the intensity of the insolation on the Faulhorn relatively to that at Brienz, 6,844 feet nearer the sea-level, varied, between 8¼ A.M. and 4½ P.M., from 1·075 to 1·345, the ratio being least at noon. The Reverend G. C. Hodgkinson, on the 14th July, found the ratio on Mount Blanc to that at Chamounix (difference 12,359 feet), between 9 hours 30 minutes and 10 hours 11 minutes, A.M., to be between 1·244 and 1·266: and Mr. Henessey found the ratio at Masuri to that at Dehra (difference 4,708 feet), on the 4th November, to decrease from 1·174 at 8 A.M. to 1·086 at noon, and to increase afterwards to 1·429 at 4 P.M. Hence, the absorption by the

[1] Bakerian Lecture, 1842, Phil. Trans., volume LXXXV, page 225.
[2] Proc. Royal Soc., volume XV, page 321.
[3] *Ibid*, Volume XIX, page 225.

lower atmosphere increases as the day progresses, subject of course to a variation with the obliquity of the incident rays and the length of their path. The results of the Faulhorn and Brienz observations have been discussed at considerable length by Principal Forbes in his Bakerian Lecture to the Royal Society in 1842, and the following conclusions arrived at (among others) :—

That the absorption of the solar rays by the strata of air, to which we have immediate access, is considerable in amount, for even a moderate thickness; that the absorption almost certainly reaches a limit, beyond which no further loss will take place by an increased thickness of similar atmospheric ingradients; and that the residual heat may amount to from a half to a third of that which reaches the surface of the globe after a vertical transmission through a clear atmosphere; that the law of absorption in a clear and dry atmosphere, equivalent to between one and four times the mass of air traversed vertically, may be represented (within those limits) by an intensity diminishing in a geometrical progression, *plus* a constant quantity, which is the limiting value already mentioned. Taking the value of the extra-atmospheric radiation as 73° (of the arbitrary scale of the actinometer), the limiting value of the solar radiation, after passing through an indefinite atmospheric thickness, is 15° 2′. The absorption in passing through a vertical atmosphere of such thickness as to exert a pressure of 29·922 (reduced) barometric inches, is such as to reduce the incident heat from 1 to ·534.

The most extensive and important observations on the varying rate of cooling in different states of the atmosphere, hitherto published, are probably those of Dr. Neumayer at Melbourne in 1858—63.[1] He placed a spirit thermometer in the focus of a parabolic mirror, directed to the zenith, and resting on a bed of non-conducting material; while it was screened on all sides around from currents of air. The observations, 4,376 in number, were made at all times of the day and night, but only when the zenith was perfectly free from visible cloud, and the shade temperature of the air and that of evaporation were observed simultaneously. The radiation observations having been reduced and tabulated in series, first, according to the increase of the vapour tension, then according to temperature, and lastly, according to the relative humidity of the air, led to the conclusion "that the absolute quantity of aqueous vapour in air is alone in itself not sufficient as a criterion for the degree of radiation. The relative humidity of the air greatly influences radiation in such manner that the greater the degree of relative humidity

[1] Phil. Mag., 1866, 3rd Ser., Volume XXXI., page 510; and Discussion of Met. and Mag. observations at the Flagstaff Observatory, Melbourne, page 114.

the less radiation is noticeable." In other words, the athermancy of the air varies with its relative humidity. The nearer it is to that state in which it begins to deposit cloud or fog, the more opaque is it to dark heat, and it is this, and not merely the absolute quantity of the vapour diffused through it, that is the determining condition of athermancy.

The discussion of observations on the nocturnal cooling of the air at Madras in 1841—44 by Captain (now General) R. Strachey,[1] and subsequently by Mr. Park Harrison,[2] lead to a similar conclusion. Selecting, as clear nights, those on which the cloud proportion was one-tenth of the expanse or less, and rejecting all others, it was found that the fall of temperature between sunset and sunrise was the greater, the lower the tension of the vapour in the air. But when, instead of the vapour tension, the mean cloud proportion was taken as the basis of the comparison, the *pari passu* variation in the fall of temperature was far more decided; so much so, indeed, as to make it probable that the tendency to the formation of cloud is the real critical condition of athermancy, and that the apparent influence of vapour tension is only a secondary condition, owing to the fact that, *cœteris paribus*, the higher the humidity of the air the higher is the vapour tension. Estimating the whole expanse of the sky, in the usual way, as 10·, it was found that an average of 0·85 of cloud reduced the nocturnal fall of temperature by more than one-fourth of that which took place under a perfectly cloudless sky.

The conclusion, then, which the present state of our knowledge seems to justify, is that both air and vapour, as compared with other gaseous bodies, are moderately good absorbers of heat, and in a nearly equal degree; but that the varying diathermancy of the atmosphere depends chiefly on the quantity of condensed vapour in it, and also, it may be added, on solid matter, dust, &c., suspended in it. Condensed water exists in other forms than as visible cloud masses. Tyndall has demonstrated that the blue colour of the sky is probably owing to condensed vapour in a very fine state of division, and that state which Roscoe speaks of as the *opalescence* of the atmosphere, may possibly arise from a similar cause. Then, again, suspended dust, such as that which constitutes the constant haze of the dry season in Upper India, is a great absorber of heat as well as of light, and doubtless plays an important part in that diurnal heating of the lower atmosphere which gives rise to the hot winds of April and May. As a general rule, liquid and solid

[1] Phil. Mag., 4th Ser., Vol. XXXII, page 64.
[2] Proc. Roy. Soc., Vol. XV, page 367.

matters are far more absorbent of radiation than the gaseous matters of the atmosphere.

26. Cooling by radiation.—It is an universal law that the readiness with which substances part with their heat by radiation, stands in a direct relation to their absorptive power. Professor Balfour Stewart's experiments have demonstrated that this law holds good in detail, and that substances which like gases, coloured glass, or reflecting and coloured bodies, absorb certain kinds of radiation selectively, also radiate those kinds selectively. Air, then, which absorbs but little heat, as compared with fluids and solids, radiates and loses heat but slowly, and hence those elevated strata of the atmosphere which are not in contact with mountains probably undergo but a small change of temperature between day and night. But rocks and soils, which are greedy absorbers of heat, and in proportion as they absorb it are also good radiators, play a very important part in the nocturnal cooling of the lowest stratum of the air, which loses heat by contact with the ground. In like manner, in the winter season, radiation from the ground is one of the chief causes of the lower temperature which then prevails over the land, bringing about that greater density in the lower atmosphere, which, in India, determines the origin of the northerly monsoon. On mountain tracts the effect of this cooling is felt in the currents of cold air which drain off the mountain slopes, and flow down the great valleys as cold winds during the night and early morning—and in the winter season, frequently throughout the day. The deposition of dew and hoar frost on the surface of leaves, grass and other good radiators, are other familiar effects of cooling by radiation.

27. Dynamic heating and cooling.—Readers of Tyndall's interesting lectures on "Heat, a mode of motion," may remember two striking and paradoxical experiments, in which, by projecting a current of air on the face of a thermopile, a heating effect was manifested in one case, and a cooling effect in the other. In the first, air was forced from a bellows; in the second, air which had been condensed in a strong metallic vessel, and, in its compressed state, had acquired the temperature of the surrounding air, was allowed to escape and produce a blast on the face of the pile. The solution of the paradox lay in the fact that air from the bellows only differed from that around by being in rapid motion, and this motion, when arrested by the thermopile, was converted into heat: in the case of the compressed air, the escaping air, before reaching the thermopile, had done work, in the act of expanding, by overcoming the pressure of the atmosphere and thrusting it aside, and the heat expended in performing this work, and therefore lost, was

greater than that reproduced from the arrested movement. These two experiments are instances of *dynamic heating* and *dynamic cooling*.

Whenever air (or, indeed, any other substance), in expanding, has to overcome resistance, the work done is represented by a loss of heat; not indeed, of necessity, by a fall of temperature, because if the expansion takes place in consequence of heating, under a constant pressure, the temperature must be rising at the same time; but the quantity of heat which it absorbs under these circumstances is greater than would be necessary to raise it to the same temperature were it not expanding against resistance. This difference is that referred to in § 18 as that of the specific heat of air at constant pressure (*i. e.*, when expanding), and at constant volume. When the air, while being heated, is contained in a close vessel, no work is done, and the heat absorbed goes simply to raise its temperature; but if it expands and remains of the same elastic pressure, a portion of the heat absorbed is used up in making room for the expansion by thrusting aside or lifting the mass that presses upon it. The ratio of this excess to the whole quantity of heat absorbed is constant, and therefore the specific heat at constant pressure bears a constant ratio to that at constant volume, *viz.*, 1·41 : 1. §§ 18, 29.

On the other hand, air which is cooling and therefore losing elastic force under a constant external pressure, has to get rid, not only of its actual heat, but of that which is developed in it by the compression it undergoes. That air which is condensed by any increase of external pressure becomes heated, is a fact familiar to any one who has ever compressed air by means of a condensing syringe, as for instance in charging the reservoir of an air-gun.

28. Joule's mechanical equivalent of heat.—The great discovery of Joule, that the fall of a mass of matter weighing 772 lbs. through a height of one foot[1] under the force of gravity at Manchester[2] will develope, when its motion is arrested, so much heat as will heat 1 lb. of water one degree Fahrenheit (*i. e.*, one unit of heat, § 17), affords the means of computing the exact quantity of heat that is developed by the compression, or disappears in the expansion of air under a given pressure. The *mechanical equivalent* of one unit of heat being 772 foot-pounds, if we multiply the pressure (estimated in pounds on the square foot) by the height through which it falls in the one case or is lifted in the other (correcting the result for any difference in gravity), and divide

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[1] Or 1 lb falling through 772 feet; in general terms, 772 foot-pounds.

[2] This is a necessary part of the definition, because the work depends on the momentum generated, or on the force employed when the mass and time are constant. This, in the case of a falling body, is gravity, and, as is well known, the force of gravity varies at different parts of the earth's surface.

this product by 772, we obtain the number of heat units that are produced or disappear. Dividing this by the specific heat of air at constant volume, and also by the weight in pounds of the air compressed or expanded, we obtain the number of degrees through which it will be heated in the one case and cooled in the other.

29. Ratio of specific heats c and c_p.—The weight of a cubic foot of air at a pressure of 30 inches and the temperature of 32° Fahrenheit has been taken (§ 2) at 565 grains. The weight, therefore, of a column of such air, 493 feet high and one square foot in section, would be 278,545 grains or 39·792 lbs. avoirdupois; and we have seen that, if the pressure on the top of such a column be equal to a barometric pressure of 30 inches, this, estimated in lbs., will be 14·735 lbs. on each square inch or 2121·84 lbs. on the square foot. Now, a column of air 493 feet high, if heated 1° Fahrenheit and allowed to expand in one direction only, will lengthen to 494 feet; and, under the conditions supposed, will lift 2121·84 lbs. one foot high, doing therefore 2121·84 foot-pounds of work. Dividing this by Joule's equivalent, 772 foot-pounds, we obtain its equivalent in heat units, *viz.*, 2·748 nearly. But by § 18, the number of heat units which will raise 39·792 lbs. of air (kept at constant volume) by 1° Fahrenheit, is $39{\cdot}792 \times {\cdot}168 = 6{\cdot}685$. The ratio, therefore, of the heat absorbed by the air, when at constant pressure, is, to that absorbed when at constant volume, as $6{\cdot}685 + 2{\cdot}748$ to $6{\cdot}685$ or $\frac{9{\cdot}433}{6{\cdot}685} = 1{\cdot}41$. This is the ratio already stated in § 27. It is easily seen that the result would be the same had we assumed any other pressure than 30 inches, for, by Boyle's law, if the quantity (mass) of air be constant, the volume will *increase* in proportion as the pressure is *reduced* and *vice versâ*; and since, by Charles' law, the expansion is a constant increment of the volume, the space through which the pressure will be lifted will *increase* in the same proportion as the volume. The product of the pressure and the space therefore is constant for the same weight of gas and the same increment of temperature.

Knowing now the ratio of the quantities of heat absorbed by a gas when heated at constant volume, and when it expands and does work at constant pressure, we can correct the provisional result obtained in § 22 for the condition which occurs in nature, *viz.*, free expansion. For we know that the heat required in the former case is to that required in the latter in the proportion of 1 to 1·41, and that for each unit of heat consumed in raising the temperature, a quantity represented by 0·41 is spent in work. But an atmosphere that is merely charged with vapour by the expenditure of one unit of heat and expands under a

constant pressure, let us say at the temperature of 80° Fahrenheit, will do only $\frac{1}{7\cdot27}$ the same amount of work, and will therefore expend $\frac{1}{7\cdot27} \times \cdot0\cdot41 = \cdot056$ of an unit nearly, absorbing a total of 1·056 units. Hence equal quantities of heat will produce expansion in the two cases in the ratio—

$$\frac{1\cdot056}{1\cdot41} \times 7\cdot27 = 5\cdot44$$

30. Convection currents.—One of the most important applications of the laws of dynamic heating and cooling in meteorology is to the case of convection currents. By convection currents are meant ascending and descending currents, which are set up in consequence of a portion of air having become, by change of temperature, either less or more dense than other parts of the same stratum, while exercising the same elastic pressure. In such case it obeys the law of floatation, and the heated air rises while cooler air descends and takes its place. That this kind of action is of high importance, and, together with its inverse action (the cooling and sinking of heavy air), is the principal cause of winds, is a fact which can scarcely be considered open to question; but a consideration of the laws of dynamic heating and cooling, and their consequences, will shew that the conditions under which convection currents can be set up are rigorously limited; and observation tells us that, in a column of dry air, or one much below saturation, these conditions are very rarely fulfilled, except on a small scale and within a small distance of the ground. This fact has been insufficiently insisted on in some of our elementary treatises on meteorology, and much erroneous reasoning has been the result of the omission.

In India, the monsoons are the consequence of convection currents on a vast scale, which, at one time of year (during the rains) are ascending, and at another time (in the cold season) descending currents, in the interior of India. To understand these fully, it will be necessary that we have a clear comprehension of all that relates to such currents; and no apology is needed, therefore, for entering somewhat at length on the subject of the dynamic cooling and heating of the air under the conditions described.

31. Dynamic cooling and heating of convection currents in dry air.—Let us consider the case of a mass of air ascending in a convection current, but neither absorbing nor losing heat (otherwise than by its own expansion) during its ascent. We have seen, § 29, that, in expanding through $\frac{1}{493}$ or ·002039 of the volume it occupies at the

freezing point, it has to do work which reduces its temperature 0·41 of a degree Fahrenheit. Therefore, its temperature will be reduced 1° (by work) when it has expanded

$$\frac{\cdot 002039}{0\cdot 41} = \cdot 004973$$

of its volume at 32°. By this reduction of temperature, its elastic pressure would be reduced by ·002036 of its pressure at 32°, supposing the volume were unchanged, and since the expansion corresponding to this temperature decrement is ·004973, which represents a further loss of elastic tension —·004966, its total loss of pressure is ·002036 + ·004966 = ·007002 = $\frac{1}{143}$ of its pressure P_0 at the freezing point. This, be it observed, is true, whatever be the initial pressure and temperature.[1]

Now, if we represent by H the height of a homogeneous atmosphere at the temperature of the freezing point, then the height h at which the ascending mass of air will be under a superincumbent pressure $\frac{1}{143}$ less than at its base will be $\frac{\mathsf{H}}{143} = \frac{26250}{143} = 183$ feet. This is constant, since H does not vary with the presssure (§ 2), and if the reduction of pressure $\frac{1}{143}$ P_0 be referred to the pressure of air at any temperature T other than that of the freezing point T_0 it must be multiplied by $\frac{T_0}{T}$ (§ 7). On the other hand H becomes $\frac{T}{T_0}\mathsf{H}$ (§ 6), and therefore the value of the product is unaltered. The decrement of 1° in 183 feet is the same as 5·46° in 1,000 feet.

Since, then, dry air, in ascending, uses up heat at the rate of about 1° in every 183 feet, it is clear that if the temperature of the atmosphere through which it ascends does not decrease at an equal or some greater rate, any mass, which, as supposed in § 30, has been so heated as to expand and form an ascending convection current, will cool more rapidly than the strata through which it ascends, and will soon be reduced to the temperature and density of the air at the same level; when its further motion will be arrested. Nay, if immediately about its initial position, the vertical decrement of temperature is not more rapid than 1° in 183 feet, it will not ascend at all;[2] and we may assert, generally, that no convection current arising from a disturbance of the vertical equilibrium

[1] This reasoning is essentially that given in Prof. Everett's translation of Deschanel's "Natural Philosophy," and is the simplest and best adapted for popular comprehension. The general problem has been treated by the help of the higher mathematics by Sir W. Thomson, Peslin, Reye, and lastly in a very exhaustive manner in its direct meteorological bearings by Dr. J. Hann, whose admirable memoir will be found in the Journal of the Austrian Meteorological Society for November 1874, Nos. 21 and 22, Volume IX.

[2] In this statement, of course, I exclude the hypothetical case of a mass of air being suddenly heated and expanded by some agent which does not affect surrounding masses.

of temperature can exist in a dry atmosphere in which the vertical decrease of temperature is less than 1° in 183 feet; *unless the ascending air is continually receiving heat from some external source.* The same law holds good, *mutatis mutandis,* for convection currents produced by the cooling and sinking of air of an upper stratum. No descending current can be set up in a dry atmosphere, unless the temperature of the air around and through which it sinks increases downwards more rapidly than 1° in 183 feet, or *unless the current is continually parting with the heat generated by its descent.*

Now, observation shews that, in India, except in the lowest strata, near the earth, and during the hottest hours of the day, the temperature decrement with altitude is never so rapid as 1° in 183 feet, and therefore merely local convection currents in a dry atmosphere arising from a disturbance of vertical equilibrium are of rare occurrence. Perhaps the only important instances are those afforded by dust storms, such as are described by Dr. Baddely. The little dust-whirls, or *devils,* so common in the hot weather, are small instances of the same phenomenon. To the reverse action, *viz.,* the heating of a descending current, Dr. Hann, however, attributes the hot dry winds felt in the Alps and some other mountainous countries, and locally known as the "Föhn."

32. Convection currents in moist unsaturated air.—Air that contains vapour, but which is below saturation, follows nearly the same law as dry air, as has been demonstrated by Dr. Hann in the paper referred to in the note to the previous paragraph. A small difference is, however, introduced by the fact that the specific heat of vapour is about twice as great as that of dry air (§ 18). The correction to be applied depends on the quantity of vapour present in the air; and the height h corresponding to a fall of 1° of temperature varies directly as the specific heat of the mixture at constant pressure. This is easily found as follows: Let p be the pressure of the moist air, and e the tension of the vapour it contains. Then, since water vapour is $\frac{9}{14.45} = \cdot623$ or nearly $\frac{5}{8}$ths the density of air at the same temperature and pressure (§ 8), the quantities (or masses) of air and vapour will be, respectively, as $\frac{p-e}{p}$ and $\cdot623\ \frac{e}{p}$. Multiplying these by the specific heats of air and vapour respectively (§ 18), and taking their sum, we have for c' the specific heat of the mixture

$$c' = 0\cdot2375\ \frac{p-e}{p} + 0\cdot4805\ \frac{0\cdot623e}{p} = \cdot2375 + \cdot0618\ \frac{e}{p}$$

and $183\ \frac{c'}{c}$ will give the height required.

33. Convection currents in saturated air.—As soon as air is saturated, so that, on further cooling, it begins to deposit a portion of its moisture in the form of cloud or fog, the evolution of latent heat introduces a new and important element into the problem, and admits of

convection currents being maintained in an atmosphere in which the vertical decrement of temperature is much less rapid than in the cases hitherto considered. Dr. Hann has discussed this case also in the paper above referred to. It is more complicated than those hitherto noticed, and the results will be best shewn in the form of a table similar to that given by Dr. Hann, and obtained by the same process of calculation.

The following Table A shews the dynamic cooling, or loss of temperature in degrees Fahrenheit, suffered by a saturated column of air at different initial temperatures t and pressures p, for 100 feet of ascent[1]; and the final column shews the elevations above sea level corresponding to the pressure p of the first column, when the temperature of the air column is 32° Fahr. :—

TABLE A.—*Dynamic cooling of saturated air in 100 feet of ascent.*

Initial pressure p.	Initial temperature $= t$ Fahr.								Elevation in feet at 32°.
	32°	42°	52°	62°	72°	82°	92°	102°	
30 inches ...	0·36	0·32	0·29	0·26	0·24	0·22	0·20	0·19	0
25 „ ...	0·34	0·30	0·27	0·24	0·22	0·20	0·19	0·18	4,470
20 „ ...	0·31	0·28	0·25	0·22	0·20	0·19	0·18	...	9,940
15 „ ...	0·28	0·25	0·22	0·20	0·18	...	...	...	16,990
10 „ ...	0·24	0·21	0·19	0·17	...	...	...	...	26,930

The use of this table will be best explained by an example. Thus, the air in a cumulus cloud, 1,000 feet above the earth, is at a temperature

[1] The figures in the table are obtained by the formula of Peslin,

$$\frac{dt}{dh} \qquad \frac{1 + r\,q\,J\,\frac{\rho}{p}}{c'\,J + r\,q\,J\,\frac{1}{e}\,\frac{de}{dt}}$$

wherein p is the initial pressure, q the weight of vapour in one cubic foot of saturated air at temperature t and pressure p, and e its elastic tension; r the latent heat of vapour at the same temperature, J the mechanical equivalent of heat $= 772$ foot-pounds, and c' the specific heat of the mixture of air and vapour. All the values are expressed in the English units of lbs. and feet, and the Fahrenheit scale of temperature: $\frac{dt}{dh}$ is the dynamic decrease of temperature suffered by the air in the unit (1 foot) of ascent, which, multiplied by 100, gives the figures in the table. Following Dr. Hann, the values of $\frac{1}{e}\,\frac{de}{dt}$ have been obtained by the help of Magnus' formula for the tension of saturated vapour, $e = 4{\cdot}525 \times 10^{\frac{at}{b+t}}$ which gives $\frac{de}{dt}\frac{1}{e} = \frac{1}{M}\,\frac{ab}{(b+t)^2}$. The values of a and b for the Fahrenheit scale are given in the text, § 9.

of 66°, the pressure being 29 inches. How high must it ascend to undergo a cooling of 10°? Interpolating for 29 inches and 66° we find the initial rate of cooling will be 0·248° in 100 feet. If this were constant, the air would cool 10° in 4,032 feet. But having ascended 4,032 feet, at a mean temperature of 61° it would be under a pressure of 21·6 only. At this pressure, and the temperature 56°, the rate of cooling according to the table is 0·244 per 100 feet. The mean of this and the initial rate is 0·246 per 100 feet, so that a cooling of 10° would take place in 4,065 feet nearly, or at a height of 5,065 feet above the ground. Hence, the initial rate is not very different from the mean rate when we consider heights of a few thousands of feet only.

The table shews that saturated air at 30 inches pressure and the temperature of the freezing point will, when ascending, cool 1° in $\frac{100}{\cdot 36} = 277$ feet, and at all lower pressures and higher temperatures even less rapidly.

The reason, then, that an ascending current of saturated air may be maintained with a vertical decrement of temperature not more rapid than that which is shewn by observation to be the normal average decrement in the atmosphere, whereas an ascending current of dry air cannot be so maintained, is that, in the former, the heat which is constantly converted into work is supplied by the latent heat emitted by the condensing vapour; whereas the latter has no such source of energy to draw upon. A descending current might equally be maintained in an atmosphere laden with fog or cloud, since in that case the heat developed by the compression of the descending air would be used up as latent heat in evaporating the cloud, but such a condition rarely occurs in nature, at least in India.

34. Energy and its transformations.—In the preceding paragraphs, we have discussed some of the more important processes by which heat operates in setting the atmosphere in motion. We have seen that the source of this heat is the radiation from the sun, that this radiation is absorbed by our atmosphere, partly in the form of sensible heat, raising the temperature and at the same time doing work by expanding the heated air and lifting the higher strata that press upon it; partly in the form of latent heat, in evaporating cloud and in raising vapour from the water expanse, and from humid land surfaces, which also adds to the volume of air, and so does work against the pressure of the incumbent mass. Whenever any movement is set up in the atmosphere against the action of gravity, some heat disappears; and whenever motion is checked or a mass of air descends under the action of gravity, heat is developed,

and must be got rid of by radiation or otherwise, if the descending current is to be maintained. On the whole, the quantities of heat absorbed and emitted are equal; for, in the long run, the generation and destruction of momentum are equal, and ascending and descending currents are mutually compensating; so that the work done against gravity by the one is equal to the work done by gravity on the other. But it is rarely, indeed, that this compensation is effected in one and the some region. Where the sun's heat falls most copiously, *viz.*, in the tropics, there do ascending currents preponderate, and where, as in Northern Asia, a broad arid expanse of land radiates its heat freely into space through the long winter nights, there and then are descending currents most active. Were it not for the heat, or, to speak more accurately, the *energy* locked up in vapour, the so-called 'latent heat' which is absorbed in evaporation and emitted when vapour condenses, ascending currents would probably be restricted to the tropics; and even there they would be comparatively insignificant in volume. But, so locked up, it is carried to distant regions, and set free in the cloud stratum that caps the Altai or the Himaláya.

The conception which, in the above remarks, is designated by the term *energy*, is one of which we must never lose sight in reasoning on physical processes. It means *the power of doing work*, which is possessed either by moving masses or hot bodies, or by any body or system of bodies, so arranged or in such a condition that, without any work being extended upon them, they may be made to yield work. Thus, a cannon ball just fired, a falling weight, a gust of wind, a mass of heated metal, the solar radiation, are instances of one class of forms of energy; a wound-up watch spring, a lifted hammer, a difference of pressure in the same horizontal plane of the atmosphere, a mass of gunpowder or a quantity of coals together with the oxygen of the air, and that which we call the latent heat of vapour, are instances of the other. The former class, in all of which there is motion, either of the mass or of its molecules, are instances of *kinetic energy*; the latter, in which the condition is one of rest, of equilibrium more or less unstable, are instances of *potential energy*. Now, the law of energy is, that the quantity of energy in the universe, the sum of all kinetic and all potential energies, is constant. The one may be converted into the other. The falling weight may lift another weight and leave it at rest, but ready to fall in its turn; the gust of wind may raise the barometric column against the action of gravity, and, once raised, it may be made so to remain by closing the mouth of the tube; and the solar radiation that is absorbed in the evaporation of water becomes latent heat; on the other hand, the watch spring may set the works in motion, the lifted hammer fall, the gun-

powder explode and drive forward a cannon ball, and the difference of atmospheric pressures set a wind in motion; but in these and all other transformations, the quantity of the one that disappears is a constant equivalent of the quantity of the other generated. Of this Joule's heat equivalent (§ 28) is an admirable example. The unit of heat as defined in § 28 is generated by arresting the movement of a mass weighing 772 lbs. that has fallen under the influence of gravity through one foot. This is its kinetic equivalent. A weight of 772 lbs. raised to the height of one foot and ready to fall, on the touch of a trigger would be its potential equivalent, and equivalents may equally be found in terms of unignited gunpowder, unconsumed coal, &c.

Now, in reasoning on questions of atmospheric physics, such as the production of winds, the transport of vapour, the generation of storms, or the simple derangement of atmospheric equilibrium of pressure, we must always ask ourselves, "Whence comes the energy competent to produce this effect?" and a due observance of this rule will frequently prevent our falling into the error of ascribing a phenomenon to an agency that is manifestly inadequate. Of this error, or what seems to me to be such, I shall give an example in treating of the causes of cyclones.

Meanwhile, we may bear in mind that all the energy, both potential and kinetic, that exists in our atmosphere (with quite unimportant exceptions) comes from the sun, and in whatever way the quantity of its radiation may vary, the movements of our atmosphere must be subject to the like variation. That it does vary to some extent, we shall see reason to infer from the facts to be recounted in another chapter.

THE PHYSICAL GEOGRAPHY OF INDIA AND ITS DEPENDENCIES.

35. Influence of geographical features on Meteorology.—The connection between the meteorology of a country and the form and clothing of its surface is in all cases very intimate, and nowhere more so than in India. Nor is this influence one-sided only; not only do the physical condition and movements of the atmosphere depend on the distribution of land and water, on the directions of mountain chains, the elevation of the land above the sea level, the nature of the soil, the presence of sandy wastes or forest-clad uplands and the like; but the fertility of the land surface itself, and, in certain cases, the very form of that surface, are in no small degree modified by the direct or indirect action of the atmosphere. The latter class of effects, indeed, pertain to the domain of the naturalist, the physical geographer, and the geologist, rather than to that of the meteorologist, and may here be passed by without further allusion. But the former are among the most important data of meteorological science, and he who would understand the observed atmospheric changes, and would trace them to their underlying causes,—who, in short, not contented with the mere registration of the statistics of meteorology and of its formal laws, would seek further to discover their rational explanation and the laws of their physical interdependence,—must possess something more than a merely superficial acquaintance with the geography of the country in which his field of work lies, and must keep its features constantly in mind when engaged in the discussion of meteorological problems.

I shall therefore preface this account of the meteorology of India with a short sketch of the physical geography of the country, more especially with reference to the form and clothing of the surface, and to those climatic features which are the average outcome of its meteorological conditions.

36. Mountain zone—Himalaya.—To begin with the mountain ranges which constitute both the political and physical boundaries of the country, on the north and north-west—the Himálaya and the Sulemán. Both these ranges are the interrupted serrated barriers of table-lands which form parts of the great east and west mountain system of the Europe-Asiatic continent; and though so different in direction (meeting, in fact, at right angles, in latitude 32°, on the 72nd meridian of longitude), they appear to be of approximately the same geological age; and, as is proved by their structure, of comparatively recent (middle and later tertiary) date. From the gorge of the Indus, between East longitude 72° and 75°, to that

of the Dihong in E longitude 95° 30′, a distance of 1,400 miles, the Himálaya is an unbroken watershed, its northern flank being drained by the upper valleys of these two rivers, which rise, within one hundred miles of each other, in the neighbourhood of the great peak of the Kailas (22,000 feet), and flow, the one to the north-west, the other to the south-east and east. After a course, in each case, of about 1,800 miles, they discharge their waters into the ocean, at the opposite angles of the Indian peninsula. From the southern foot of Kailas, a third great river, the Sutlej, rises in the sacred lakes of Mansaráwar and Rakas Tál, and after a course of 150 miles to the north-west, in a deep gorge through the elevated plain of Gugé, it breaks through the main mass of the mountains, and joins the Indus near Mithankot, at the southern extremity of the Punjáb. Although, therefore, the Himálayan watershed is continuous through the peak of Kailas, the mountain mass is divided by the Sutlej into two very unequal divisions,—that to the north-west being the smaller but of more complex physical structure, and consisting of several sub-parallel and intersecting ranges of great elevation, while that to the south-east and east consists essentially of a linear series of elevated peaks, which, with their subordinate spurs, stand out to the south of the watershed, and are separated by the valleys of the rivers that drain their northern as well as their southern slopes.

The average elevation of the Himálaya may be taken at not less than 19,000 feet, and therefore equal to the height of the lower half of the atmosphere; and, indeed, few of the passes are under 16,000 or 17,000 feet. Across this mountain barrier, there appears to be a constant flow of air northwards to the arid plateau of Tibet. It is probable that this is more active in the day-time than at night, since the observed diurnal variation of the barometric pressure on the lower plains and at hill stations, as well as that of the winds on the high plains and passes, seems to indicate that the transfer of the portion of the higher atmosphere from over the low plains to the mountains, and even to the lower hills and table-lands of the peninsula, takes place as a secondary effect of the diurnal solar action, § 79. There is no reason to believe that any transfer of air takes place across the Himálaya in a southerly direction; unless, indeed, in those most elevated regions of the atmosphere which lie beyond the sphere of observation; but a nocturnal flow of cooled air from the southern slopes, is felt as a strong wind, where the rivers debouch on the plains, more especially in the early morning hours; and it probably contributes, in some degree, to lower the mean temperature of that belt of the plains which fringes the mountain zone.

The Eastern Himálaya presents many points of contrast with the western parts of the range which must strike even the least observant.

The slopes of the Sikkim and Bhotán hills, where not denuded for the purposes of cultivation, are clothed with a dense impenetrable forest, which, at the lower levels, abounds in figs, rattans and genera characteristic of the tropics, and of a humid climate; and, at higher levels, consists of oaks, chestnuts, magnolias, &c., of the most luxuriant growth. A scarped face of bare rock is rarely, if ever, to be met with in the lower and outer ranges; and when, as frequently occurs in the rainy season, the hill-side is scored and laid bare by a recent landslip, the disrupted mass shews how deeply the heavy rain and decaying vegetation of the surface have carried decomposition into the heart of the mountain.

In the Western Himálaya, on the other hand, the outer ranges are more thinly clad with forest, especially on their western and southern faces; and naked, precipitous crags are of constant occurrence. The vegetation of the lower and warmer valleys and of the fringing slope (the Terai) is comparatively thin, and such as characterises a warm but dry region; and pines of several species form a conspicuous feature of the landscape, at lower levels. It is chiefly the outer ranges that exhibit these contrasted features; and they depend partly on the difference of latitude, but mainly on that of the rainfall. In Sikkim and Bhotán this is abnormally copious, and is discharged full on the face of the range. As the chain recedes to the north-west, the greater is the distance to be traversed by the vapour-bearing winds in reaching it, and the more easterly is their direction; since, whether coming from the Bay of Bengal, or from the Arabian Sea, on reaching the Gangetic valley, they turn and blow more or less parallel to its axis and that of the mountain range.

37. Mountain zone—Suleman range.—West of the Indus, and parallel with that river, the Sulemán range runs north and south, separating the plains of the Punjáb from the Cabul plateau and Sewestán. The angle that it forms at its junction with the Himálaya is occupied by a low table-land, locally termed the Potwar, averaging somewhat less than 2,000 feet above the sea, and cut off from the lower plains by the barren escarpment of the Salt range.

The Sulemán range rises abruptly from the plain of the Indus valley. Its highest peaks are below 12,000 feet, and the elevation of the range declines to the south, where it constitutes the frontier of Sewestán. About opposite to the junction of the Sutlej and Indus, at Mithankot, it turns westward, bounding the plain that leads up to the Bholan Pass; and from this pass southward, the Khirthar range, *en échelon* with the Sulemán, and from 3,000 to 7,000 feet in height, bounds the highlands of Khelat and Bálúchistán, and skirts the Indus valley nearly to its termination at Cape Monze. All this country is characteristically arid. The

mountains present a bare surface of tertiary rocks, in which the geologist can trace the outcrops of the several formations as in a diagram section. Dry winds from the desert tracts of Persia and Bálúchistán predominate throughout the year; and while the scanty cultivation of the hills is dependent on the winter snows, or the rare showers which reach them from the eastward, or on the supply of the larger local streams, the lower plains would be uninhabitable but for the fertilising irrigation furnished by the great river that traverses them.

38. Indus plains and Thur desert.—At the foot of the great mountain barrier, and separating it from the more ancient land which now forms the highlands of the peninsula, a broad plain, for the most part alluvial, stretches from sea to sea. On the west, in the dry region, this is occupied partly by the alluvial deposits of the Indus and its tributaries, and the saline swamps of Kach, partly by the rolling sands and rocky surface of the desert of Jesalmir and Bikanir, and the more fertile tracts to the eastward of this watered by the Lúnai. Over the greater part of this region, rain is of rare occurrence; and, not infrequently, more than a year passes by, without a drop falling on the parched surface. On its eastern margin, however, in the neighbourhood of the Aravalli hills, and again in the Northern Punjáb, rain is more frequent, occurring both in the south-west monsoon, and also at the opposite season in the cold weather. In this part of the Punjáb a belt of about 100 miles in width produces luxuriant crops of wheat; and, since the British occupation of the province, the planting of trees has been vigorously encouraged, with the aid of irrigation. The result of the extension of cultivation, as I am assured by old residents, has been a certain amelioration of the climate. Dr. Henderson lately informed me that, within his experience of the last twenty years, dust-storms have become far less frequent than formerly, and this fact has been corroborated by other informants. Whether or not the average rainfall has been affected by the change, is a point on which as yet I have been unable to obtain trustworthy evidence.

Southward from Lahore and the Salt range, cultivation is restricted to those tracts which are irrigated from the river or from wells, and the Doábs of the five rivers are for the most part occupied by a thin scrub of *Capparis* and other desert plants. At Sírsa and Mooltan, the average annual rainfall does not exceed 6 inches.

39. Gangetic plains.—The alluvial plain of the Punjáb passes into that of the Gangetic valley without visible interruption. The ridge of older rocks which runs up from the plateau of Rájpútána, in the prolongation of the line of the Aravallis, dies out at Delhi; and to the north of this city, the watershed of the two great river systems is only

the highest part of the plain, elevated from 800 to 1,000 feet above the sea. It slopes gradually from north-west to south-east, and from the foot of the Himálaya to the main streams of the Jumna and the Ganges, which, throughout their course, flow along its southern margin, and receive successive affluents equal to or even greater than the original stream, in the Chambal, the Gogra, the Gundak, the Son, and the Khussi.

Up or down this plain, at opposite seasons, sweep the monsoon winds in a direction at right angles to that of their nominal course, and thus, vapour which has been brought by winds from the Bay of Bengal, is discharged as snow and rain on the peaks and hill sides of the Western Himálaya. Nearly the whole surface is under cultivation, and it ranks among the most productive as well as the most densely populated regions of the world. Wheat is the great staple product of the plain, more especially of the *Bhángar* land, or that which lies above the flood level of the rivers. Only in Lower Bengal, and on the strips of *Khádir* or flooded land which fringe the larger streams, is rice the more important food-grain. The rainfall diminishes from 100 inches at the south-east corner of the Gangetic delta to less than 30 inches at Agra and Delhi, and there is an average difference of from 15 to 25 inches between the northern and southern borders of the plain.

40. Eastern Valleys—Assam and Cachar.—Eastward from the delta, two alluvial plains stretch up between the hills that connect the Himálayan system with that of the Burmese peninsula. The first, that of Assam and the Bráhmaputra, is long and narrow, bordered on the north by the Himálaya, on the south by the lower plateau of the Gáro, Khási, and Nágá hills. The other, short and broad, and in great part occupied by swamps and *jhils*, separates the Gáro, Khási, and Nágá hills from those of Tipperah and the Lushai country. The climate of these plains is damp and equable, and the rainfall is prolonged and generally heavy, especially on the southern slopes of the hills. A meteorological peculiarity of some interest has been noticed, more especially at the stations of Sibságar and Silchár, *viz.*, the great range of the diurnal variation of barometric pressure during the afternoon hours; which is the more striking, since at Roorkee, Lahore, and other stations near the foot of the Himálaya, this range is less than out in the open plains. A similarly exaggerated range is, however, exhibited by Leh in the Indus valley, as appears from a few days of hourly observations recorded by Captain Trotter and Dr. Scully in September 1874 and 1875; and it would seem from these instances that the daily fall is exaggerated in narrow deep valleys, but reduced at stations situated on the margin of a broad plain immediately below a lofty hill mass. These facts, and the well-known peculiarity of the

oscillation on elevated mountain peaks and ridges, together with the oft-described phenomenon of the strong afternoon winds which blow up through the high passes and across the elevated plains of Rúpshu and Ladák, have led me to the conclusion put forward on a previous page, and discussed at length in §§, 76, 96, 98, *viz.*, that the effects of the diurnal solar heating of the atmosphere is to cause a transfer of air from the plains and deep valleys to the hills during the hotter hours, similar to that which, as I have elsewhere shewn, appears to take place between land and sea.

41. Peninsular highlands—Satpura range.—The highlands of the peninsula, which, as I have already mentioned above, are cut off from the encircling ranges by the broad Indo-Gangetic plain, are divided into two unequal parts, by an almost continuous chain of hills, running across the country from west by south to east by north, just south of the Tropic of Cancer. This range of hill country, it has been suggested by Prof. H. H. Wilson, is probably identical with the Vindhyans of ancient authors, which separated Hindústán from the Dakhan; although that name, on our modern maps, is applied to the less important escarpment which bounds the Nerbudda valley on the north. It is not of uniform geological structure throughout; the western part, the Sátpúrá range, consisting of thick beds of volcanic rock of later cretaceous or cretaceo-tertiary date; while the eastern half, comprising the plateau of Chútia Nágpúr and Házáribágh, is composed of crystalline metamorphic rocks, which are apparently the axis of a chain of very high antiquity. At the present time, the whole chain, however, may be regarded as a single geographical feature, forming one of the principal watersheds of the peninsula,—the waters to the north draining chiefly into the Nerbudda and the Ganges; those to the south, into the Tapti, the Mahánadi, and some smaller streams. In a meteorological point of view, it is of considerable importance. It does not, indeed, form the boundary between the easterly summer monsoon of the Gangetic plain and the westerly monsoon of the peninsula proper, which crosses the plateau of Málwa and Bághalkhand to the north of the range; but, together with the two parallel valleys of the Nerbudda and Tapti, which drain the flanks of its western half, it gives, at opposite seasons of the year, a decided easterly and westerly direction to the winds of this part of India, and condenses a tolerably copious rainfall during the south-west monsoon. Most parts of the range are still covered with jungle, which includes important forests of sál (*Shorea robusta*), and it is inhabited chiefly by aboriginal tribes of non-Aryan descent.

42. Northern plateau—Malwa and Baghalkhand—Aravallis.—Separated from this chain by the valley of the Nerbudda on the west, and that of the Son, a tributary of the Ganges, on the east, the plateau

of Málwa and Bághalkhand occupies the space intervening between these valleys and the Gangetic plain. The whole drainage of this plateau, with an unimportant exception at its south-western corner, is thrown off northwards; some of the streams that rise on the very verge of its southern escarpment and within a few miles of the main stream of the Nerbudda being affluents of the Ganges. The surface is an undulating plain with occasional hills, the highest of which does not exceed 2,500 feet. The south-western part is covered by sheets of volcanic rock, of the same kind that composes the Sátpúrá range; and the remainder of the plateau is formed by very ancient sedimentary rocks (sandstones, shales, and limestones) of unknown date, or of the still older crystalline rocks on which these rest. The former of these are exposed over the eastern half of the plateau, where the several divisions of the formation crop out successively, forming a concentric series of bold escarpments from Jubbulpore eastwards. Westward from Jubbulpore the last of these forms the continuous south margin of the plateau, and is that known as the modern Vindhya. On its western edge, the plateau terminates against the Aravalli hills, an apparently ancient range of crystalline rock, which runs from near Ahmedabad up to the neighbourhood of Delhi; and includes one hill, Mount Aboo, over 5,000 feet in height. This range exerts an important influence on the direction of the wind, and also on the rainfall. At Ajmir,—an old-established meteorological station at the eastern foot of the range,—the wind is predominently south-west; and here and at Mount Aboo, the south-west monsoon rains are a regularly recurrent phenomenon; which can hardly be said of the region of scanty and uncertain rainfall which extends from the western foot of the range, and merges in the Bikanir desert.

43. Southern plateau—Dakhan, Mysore, &c.—The peninsula south of Sátpúrá consists chiefly of the triangular plateau of the Dakhan, terminating abruptly on the west (in the Sahiyadri range or Western Ghâts), and shelving to the east, on which side its hill boundary (the Eastern Ghâts) is somewhat discontinuous. The whole is surrounded by a fringe of low country, which, on the west coast, is narrow and somewhat rugged; on the east coast flatter and irregular in breadth. Like the northern plateau, that of the Dakhan does not extend quite up to the Sátpúrás; at least on the western side. The combined valleys of the Tapti and Púrna, occupied by the flat cotton soil plains of Khandesh and Berar, intervene between the mountain axis and the plateau. At the upper extremity of the Púrna valley, the flat plain of the Berars passes without interruption into that of the tributaries of the Godávari, which extends far down the course of that river. This is the lowest part of the

plateau; Nágpur, which is on the watershed of the Wardha and Wain-Ganga, being only a little more than 1,000 feet above the sea. Eastward from Nágpur and the Godávari valley, the country is for the most part hilly, but includes an extensive plain (nearly encircled by hills) on the Upper Mahánadi, known as the district of Chhatisgarh. On this plain is situated the station of Raipur, at an elevation of 960 feet; and 150 miles further to the east, and on the main stream of the Mahánadi, is the station of Sambalpur, at 457 feet. Beyond Sambalpur, the river traverses a broad tract of a wild hilly country, which extends, parallel with the coast, from the highlands of Chútia Nágpúr down to the delta of the Godávari, and forms part of the Eastern Gháts. The hills are generally composed of the old crystalline rocks, and in some cases rise to heights of 3,000 feet and nearly 4,000 feet, but for the most part are much lower. They include some of the wildest and least known country of India. At Cuttack, the river Mahánadi issues from the hills through a narrow gorge, and enters on its delta, which forms part of an alluvial plain extending northward to that of the Ganges.

The valley of the Godávari and its tributaries coincides with a broad depression, which slopes down gently from Nagpúr to the sea. West and south from this valley system, the elevation of the country is greater. On the margin of the Gháts, its average height is not below 2,000 feet, and the fringing range includes some hills over 4,000 feet in height. The surface of the plateau declines somewhat to the Tangabhádra, a large tributary of the Kistna, but rises again to the south to form the table-land of Mysore. Bellary, at 1,450 feet, is not far to the south of the above-named river; while Bangalore, at 3,000 feet, is situated on one of the highest parts of the Mysore plateau.

This central part of the plateau is formed chiefly of ancient, crystalline (metamorphic) rocks. Except where under field cultivation, it is a bare grassy country, with a gently undulating surface, a ridge of rocky hills or a cluster of bold and strangely shaped tors here and there rising above the general level. The Kistna valley, which is in great part excavated through ancient stratified rocks resting on the gneiss, is very similar in character, except where the river breaks in picturesque gorges through the hill range east of Karnúl; while, north of Belgaum, the rock formation is one of unbroken sheets of basaltic lava and other volcanic rocks; and the characteristic low flat-topped hills, with scarped or terraced sides, rise from the general level of the plateau and run up as low spurs to the culminating ridge of the Gháts.

This plateau is swept by the south-west monsoon, but not until it has surmounted the western barrier of the Gháts; and hence the

rainfall is, as a rule, light at Poona and places similarly situated under the lea of the range, and but moderate over the more easterly parts of the plateau. The rains, however, are prolonged some three or four weeks later than in India to the north of the Sátpúrás, since they are brought by the easterly winds, which blow from the Bay of Bengal in October and the early part of November; when the recurved southerly wind ceases to blow up the Gangetic valley, and sets towards the Carnatic. This was formerly thought to be the north-east monsoon, and is still so spoken of by certain writers; but the rainy wind is really a diversion of the south-west monsoon.

44. Eastern Ghats.—Southward from the combined delta of the Godávari and Kistna, nearly to the latitude of Madras, the central plateau is flanked on its eastern border by a triple range of hills, formed of rocks similar to those which occupy the valley of the Kistna between Shahabad and Belgaum. They are for the most part bare and rocky, and the station of Kadapah, which is surrounded by these hills, is notorious as one of the hottest in the Madras Presidency. A little to the north of Madras, the Eastern Gháts trend off to the westward, bounding the high plateau of Mysore; and at their junction with the Western Gháts, rises the bold triangular plateau of the Nilgiri hills; the highest point of which, Dodabetta, is not less than 8,640 feet above the sea. On this peak, a meteorological observatory was formerly established, and its work is well known through the publications of Colonel Sykes and Mr. Taylor. It has been discontinued for some years, and the military station of Wellington (6,200 feet) (formerly called Jakatalla), at its eastern foot, is now the meteorological station of these hills.

45. Southern hill groups.—The hill country does not terminate at the Nilgiris, but is continued to the south by the Anamullais, Pulnies, and Travancore hills, some of which rival the Nilgiris in height; and include Agastyamullai, which, *as a meteorological station, has become* famous through the labours of Mr. Broun. These hills are, however, separated from the Nilgiris by a broad depression or pass known as the Pálghát gap, some 25 miles wide, the highest point of which is only 1,500 feet above the sea. This gap affords a passage to the winds, which elsewhere are barred by the hills of the Ghát chain. The country to the east of the gap receives the rainfall of the south-west monsoon; and during the north-east monsoon, ships passing Beypoor meet with a stronger wind from the land than is felt elsewhere on the Malabar coast. According to Captain Newbold, this gap "affords an outlet to those furious storms from the eastward which sweep the Bay of Bengal, and, after traversing the peninsula, burst forth through it to the neighbour-

ing sea." The station of Coimbatoor is situated near the eastern entrance of the Pálghát gap, under the lea of the last outlying ridges of the Nilgiris.

46. Konkan and Malabar.—The strip of low country that fringes the peninsula below the Ghâts has already been briefly adverted to. Along the west coast it is narrow, and tolerably uniform in width, rocky, and well watered from the Western Ghâts, but traversed only by small rivers. The rainfall being heavy and the climate warm and damp, the vegetation is dense and characteristically tropical; and the steep slopes of the Ghâts, where they have not been artificially cleared, are densely clothed with forest. The coast of Malabar and Travancore is fringed with sand-spits, enclosing backwaters, which are so connected as to afford a very complete system of inland navigation.

47. Eastern fringing plain.—On the east coast, the fringing plain forming the province of the Carnatic, as far north as Madras, occupies from one-third to one-half the width of the peninsula, and extends up the valley of the Káveri to the foot of the Nilgiri hills, where it is nearly 2,000 feet above the sea. North of this river, a cluster of detached hill groups, some of them 4,000 or 5,000 feet in height, occupy the centre of the peninsula, standing out in advance of the Eastern Ghâts. At the entrance of one of the gorges or passes between these hills, nestles the station of Salem; while Trichinopoly lies 20 miles from their south-east corner, at the head of the Káveri delta. This delta constitutes the rich province of Tanjore; rich in virtue of its elaborate system of irrigation. It is not a swamp, however, but an upraised delta, every part of which is well elevated above sea-level; while, along the coast, it presents, at some points, a little low cliff of alluvial deposits, now undergoing slow erosion by the sea.

Immediately north of Madras, the coast plain of the Páyen Ghát is contracted to little more than 30 or 40 miles in width; and thence to the delta of the Krishna and Godávari, it extends along the foot of the Nullamullai hills, with an average breadth of not more than 50 miles. The coast plain north of the Godávari is here a mere strip, extending along the foot of the wild hills, that border the state of Jeypore and run up thence to Cuttack. At Vizagapatam itself, and for some miles to the south, the coast is formed by a rocky ridge which runs parallel to the line of the Ghâts; but, in general, the whole of this coast line, from Cape Comorin to the mouth of the Hooghly, is a low, alluvial flat, bordered by a strip of sand.

I have now completed my description of the peninsula, which, with the alluvial plain on the north, constitutes India Proper. The Eastern

Peninsula, and certain of the neighbouring islands are, however, now included in the general meteorological scheme, and a few lines must therefore be devoted to their physical geography also. The island of Ceylon may also be included, since its meteorology is inseparably connected with that of India.

48. Ceylon.—The general character of Ceylon has been admirably described by Sir Emerson Tenant. It lies to the east of Cape Comorin, its west coast being almost in the same longitude as the east coast of the peninsula between Negapatam and Pondicherry; and the intervening sea, called the Gulf of Manaar on the south, and Palk's Straits on the north, is almost bridged by a remarkable chain of coral reefs and islands, which practically close the channel to navigation. The north of the island, as well as a part of the mainland opposite, is formed of upraised coral reef: indeed, the whole of Ceylon affords indications of a recent elevation of the land. The northern half of the island is a plain of the older crystalline rocks, still much covered with forest, while the central part of the southern half is occupied by a table-land of similar geological structure, with lofty hills which rise to more than 7,000 feet, and, on their western face, are clad with dense forest, except where cleared for the coffee cultivation. The eastern part of the plateau, under the lea of the loftier hills, like the corresponding part of the Nilgiris, consists, however, of open, rolling, grassy downs, with forest in the hollows and valleys. To the south and west of the hills, the country is rugged and hilly down to the coast. The rainfall is here frequent and heavy; and the temperature being high and equable, the vegetation is dense and very luxuriant, such as is characteristic of islands in tropical seas, and also of the coast of Travancore. The plains on the east coast are drier, and both in climate and vegetation bear much resemblance to those of the Carnatic. When the south-west monsoon is blowing in May and June, discharging torrents of rain on the forest-clad spurs and slopes that face to windward, the contrast presented by the eastward face of the same hills is very striking, and the two phases of climate are sharply demarcated. Nuwara Eliya, at 6,200 feet, day after day, and even week after week, lies under a dense canopy of cloud, which shrouds all the higher peaks, and pours down almost incessant rain. But let the traveller leave the station by the Badulla road, and, crossing the *col* of the main range, at the distance of two or three miles from Nuwara Eliya, begin the descent towards Wilson's bungalow; and he emerges on a panorama of the grassy downs of the lower hills, bathed in dazzling sunshine; while, on the ridge above, he sees the cloud masses ever rolling across from the westward, and dissolving away in the drier air to leeward. Hence, the east and west coasts of

the island are as strongly contrasted in climate as those of the southern extremity of the peninsula.

49. Burmese Peninsula — Mountain chains.—The leading physical features of the Eastern Peninsula, or, at least, of that part of it with which we are here concerned, are comparatively simple. Beyond the extremity of Upper Assam, where the more easterly tributaries of the Brahmaputra issue from the gorges of the Abor hills, a series of sub-parallel or slightly diverging ranges run out to the southward, dividing and draining into the valleys of the Barák, the Irawadi and its tributaries, the Salwin, and the Mekhong or Cambodia river. The westernmost of these ranges is the Patkoi, which separates the British territory of Assam from Upper Burma, and further south divides up into the Khási and Gáro hills, the Barril, and the Arakan Yoma or coast range. The first separates the Assam and Cachar valleys and has already been noticed; the second divides Cachar from the Munipur valley; and the last, rising to a height, in some places, of 5,000 feet, runs down to Cape Negrais, separating the valley of the Irawadi from those of the smaller streams that drain the province of Arakan. At Cape Negrais it dips beneath the sea, but the chain of reefs and islands that carry on its line to the southward, the Alguada reef, Preparis, the Great and Little Cocos, the Andamans and Nicobars, may be considered as emerging summits of the sub-marine portion of the same chain. On these islands, two observatories have been established, *viz.*, at Port Blair and Nancowry. The western face of the Arakan Yoma, like that of the Indian Western Gháts, is exposed to the full force of the south-west monsoon, and receives a very heavy rainfall. At Sandoway this amounts to 250 inches. It diminishes to the northwards; but even at Chittagong it amounts to not less than 100 inches on an average. The range is thickly clothed with forest or dense growths of bamboo, some of the higher peaks only being covered with grass. The coast of Arakan is rocky, and between Sandoway and Akyab, is fringed with islands, which appear to be the sub-marine continuation of the subordinate parallel ranges that border the valley of the Koladyne.

The Pegu Yoma, which bounds the Irawadi valley on the east, or at least its more southern portion, is a lower range than the above. In British Burma it does not exceed 2,000 feet in height. This is in latitude 17°55′; and thence up to the frontier of Ava, its height varies between 800 and 1,200 feet. Further north, however, to the east of Ava, the mountains forming the eastern watershed of the Irawadi rise into greater eminence, and to the east of Bhamo, in the Kakhyen hills, attain to a height of 5,000 or 6,000 feet, running north-east and south-west, and, according to Dr. Anderson, 25 miles in breadth.

50. Irawadi valley.—The valley of the Irawadi, lying between these chains, consists of plains intersected by low, isolated hill ranges, chiefly running north and south, and confining the river in a great part of its course to narrow but deep channels. Elsewhere it opens out to a broad expanse of water, which, at Bhamo, 600 miles from the sea, is 1½ miles in width in the rains, and not less than 1 mile in the dry season.[1] The country around Ava, as well as the hill country to the north, is the seat of occasional severe earthquakes, one of which destroyed Pagan in 1839; and two large but extinct volcanoes have been described by Mr. W. T. Blanford and Dr. Anderson, *viz.*, Puppa Doung below Ava, and Hawshuenshan in the neighbourhood of Momein. The general meridianal direction of the ranges and valleys determines the direction of the prevailing surface winds, this being, however, subject to many local modifications. But it would appear from Dr. Anderson's observations of the movement of the upper clouds, that, throughout the year, there is, with but slight interruption, a steady upper current from the south-west, such as has been already noticed over the Himálaya. The rainfall in the lower part of the Irawadi valley—*viz.*, the delta and the neighbouring part of the province of Pegu—is very heavy; and the climate is very mild and equable at all seasons But higher up the valley, and especially north of the Pegu frontier, the country is drier, and is characterised by a less luxuriant vegetation and a retarded and more scanty rainfall. Very little that is systematic, and at the same time trustworthy, has yet been put on record respecting the meteorology of Burma.

[1] This description is chiefly quoted from Dr. Anderson's Report on the Mission to Yunan.

RADIATION AND TEMPERATURE.

51. Characteristics of Indian Meteorology.—In entering on the subject of the Meteorology of India, we must dismiss from our minds much that constitutes the mental stock-in-trade of the European meteorologist. Of polar currents, properly so-called, we know nought in India. Violent storms, other than north-westers and similar local disturbances, are, with us, rare and exceptional phenomena, not familiar and frequent visitants; and instead of their coming upon us unawares, from regions beyond our ken, at uncertain times and seasons, we can tell beforehand what is the numerical probability of a storm in any given month; and, with a somewhat more extended telegraphic system[1], we might watch their generation and growth, their decay and final extinction, all within the area of our possessions and their included seas. Order and regularity are as prominent characteristics of our atmospheric phenomena, as are apparent caprice and uncertainty those of their European counterparts.

52. The primary contrast of land and water—Monsoons.—In order to give the reader, at the outset, some general conception of our meteorological position, I will recall and develope the statement made in the introductory chapter, that India, together with the circumjacent seas, is, in the main, a secluded and independent arena of atmospheric action. The peninsula, and the adjoining plains and plateaux south of the Himálaya, together with the North Indian ocean, constitute a system, between which there is a constant interchange of winds; and the salient features of the local meteorology depend on the contrasted conditions of these two tracts and of the several sub-divisions of India itself. Taken together, they constitute an independent sub-division of the Asiatic monsoon region, having peculiarities of its own. The Asiatic monsoons, as I have elsewhere pointed out, consist, in fact, not of one current flowing alternately to and from Central Asia, but of several currents, each having its own land centre: and the centre which, at opposite seasons of the year, is alternately the source and goal of the Indian monsoons, lies to the south of the Himálayan chain. At two seasons of the year, *viz.*, in the months of March, April, and May, and again in the months of October and November, that is to say, at the change of the monsoons, the interchange of air currents between land and

[1] Were there a telegraph line to Port Blair and the Nicobars, and one to False Point, it would be almost impossible for a cyclone to be formed (except, perhaps, in the south-west or extreme south of the Bay) without our knowledge.

sea is, in a great measure, restricted to India and its two seas, and has but little concern with the region south of the equator. But a few weeks before the solstices, and two or three months afterwards, these currents are continuous across the equinoctial line; connecting the Indian wind system with those of the Sunda Islands and of Australia, and, at one season, with the trade winds of the South Indian ocean. These are the monsoons, as known to sailors. In India itself, the period of transition between the north-easterly or winter monsoon and the south-westerly or summer monsoon is much longer than that of the opposite change, and presents marked characteristics of its own, which justify its being distinguished as a third, *viz.*, the hot season. In extra-tropical India, the transition from the south-west monsoon or the rains to the cold season is tolerably abrupt; and only in Southern India and Ceylon is it marked by peculiar features, being the chief rainy season of the Carnatic.

Thus, the predominating feature of Indian meteorology is the semi-annual reversal of the wind system; and in the causes which bring about this reversal, and in the associated phenomena, we have a field of study, second in interest to none in the whole range of meteorological science.

53. Cause of the Monsoons.—The primary cause of the annual reversal of the monsoons is the variation of the quantity of solar heat received by the land surface of India, according as the sun is in north or south declination. This difference is not directly shown by the sun thermometer nor even by the actinometer, for both these instruments present the same surface normal to the sun's rays, whatever be his altitude in the sky; and, as may be seen on looking through any register of sun-thermometer temperatures, the excess of sun over shade temperatures is nearly the same at opposite seasons of the year, provided the sky is equally clear. Such difference as may appear when the solar intensities on equally clear days at mid-summer and mid-winter are compared, is due to the greater thickness of the atmosphere traversed by the solar rays, when his declination is low.

54. Annual variation of insolation.—The general law relative to the quantity of the sun's heat incident at any given moment on a given area, say a square foot of level surface, is that it is inversely as the square of the earth's distance from the sun; and, disregarding the atmospheric absorption, directly as the sine of the sun's altitude. The first is simply an application of the well-known law which expresses the ratio of the surface of a sphere to its radius; the second will be

readily understood from the accompanying diagram [Fig. 1]. Let AB be a portion of the earth's surface warmed by a column of solar rays, falling, in the one case at the angle α, and in the other at that of α', which angles are those of the sun's altitude at different times; the quantity received by the surface AB in an unit of time (for instance a second or minute), is directly as the diameter CB or C′B of the column; and—

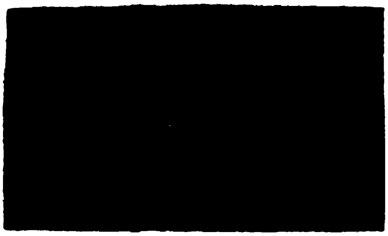

Fig. 1.—Diagram illustrating the law of solar intensity.

$$CB = AB \sin \alpha$$
$$C'B = AB \sin \alpha'$$
$$\text{whence } CB : C'B :: \sin \alpha : \sin \alpha'$$

At places on the Tropic of Cancer, which traverses India, passing about 60 miles north of Calcutta, the altitude of the sun is 90° (or vertical) at noon on the 21st June, and 43° 5′ at noon on the 21st December; and the relative quantities of heat received on a level surface, at these two instants, are, therefore, as sin 90° to sin 43° 5′, or 1 : 0·683. This ratio is, indeed, diminished nearly in the proportion of $\frac{9667}{1\cdot0388}$ owing to the eccentricity of the earth's orbit and the greater distance of the sun at mid-summer than at mid-winter; so that it is more nearly 1 : 0·730 or approximately 4 : 3. But since the quantity of heat received in a day depends, not only on the momentary intensity of the heat, but also on the length of the day, these figures are far from representing the real difference in the solar effect. The calculation of the actual difference has been made by Lambert, Poisson, and Meech. The latter has given the results for different latitudes and times of year, in the form of a table, in which, assuming that the heat shed on any place on the equator, during a day at the equinox, would produce a mean temperature of 81·5°, the quantities of heat received by other places, on different days of the year, are expressed by temperatures proportional thereto. By interpolating for the latitude of the tropic and for the longest and shortest days, we find, from this table, that the heat received on the summer solstitial day is represented by 86·3°; and that on the winter solstitial day by 51·4°—a proportion nearly as 5 to 3. But the same table shews that, on the average of the summer,—that is, from the 1st May to the 15th August,—the greatest quantity of heat falls between 30° and 40° north latitude; or, if we take only the month of June and the first half of July, it is greatest in the arctic regions, and, next thereto, in a zone between 40° and 50°

north latitude. If, then, the temperature of a place, on any given day or week, were to vary directly as the quantity of solar heat then falling on it, the average highest summer temperature would be between 30° and 40° latitude; and that of the six weeks, nearest the equinox, in the arctic regions; (indeed, at the north pole.) But we have seen, in a preceding chapter, that heat falling on a water surface is largely used up in evaporating the water; and further, that owing to the high specific heat of water, its temperature is raised but little as compared with that of a land surface. Hence a water surface changes its temperature but slowly[1]; and we may expect that the variations of temperature will coincide with those of the incident solar heat, only on an extremely dry land surface; and also, it may be added, on one protected from foreign influences, (such as marine currents and winds from cooler or hotter regions.) Now, on the plains of Northern India south of the mountain zone, and again to the north of that zone, in Turkestan and the Gobi desert, these conditions are fulfilled to a remarkable degree: (on the mountain zone itself, the snows form a disturbing element.) Accordingly, we find that the highest mean temperature prevailing in any part of India, during the months of June, July, and August, is that of the Punjab, in the comparatively rainless tract about Mooltan, Montgomery, and Dera Ismail Khan; which last is in latitude 32°. It is equally dry and rainless in Sind and in the Bikanir and Jesalmir deserts; but these, being to the south, are some few degrees cooler. On the other hand, in June, the temperatures of Lahore and Ráwalpindi, which are further north—the latter being in latitude 34°,—exceed those of Mooltan and Dera Ismail Khan; but, in July and August, they are somewhat mitigated by the discharge of the summer rains; which, if scanty as compared with those of the Eastern Himálaya, are still sufficient to exert an appreciable influence on the temperature of the sub-montane belt. Crossing the mountains and proceeding still further north, we leave behind us the vapour-bearing winds of the monsoon; and in Yarkand, in latitude 38°, we find that—although 4,000 feet above the sea-level (which represents an average temperature reduction of 10° or 12°), and although, in that season, the temperature of the cultivated and inhabited belt at the foot of the mountains is probably somewhat reduced by evaporation from the irrigated fields around[2]—that of July (judging from the registers of one year) is not less than 81·7. Even in the damp

[1] In illustration of this may be cited the case of the North Atlantic, where, midway between Africa and America, the line of highest temperature in July is not more than 6° or 8° to the north of its mean annual position.

[2] Indian Meteorological Memoirs, volume I, page 58.

climate of Assam and Eastern Bengal, the direct solar influence manifests itself by raising the temperature of the upper part of the valley in latitude 26° and 27° above that of Silchar in 25°, and still more above that of the equally humid parts of Burmah (Rangoon, Moulmein, &c.).

Herein, then, lies the primary cause of the summer monsoon; in the fact that the most northern part of India is included in that zone of the earth's surface, which, during the summer months, receives the greatest proportion of the sun's heat; and which, being at the same time a land surface, acquires therefore a proportionally high temperature.

55. Relations of air temperature to insolation. Hot season.—Very instructive, in this connection, is the northward progression of the region of highest temperature, as the sun ascends in declination from March to June. In the first of these months, the hottest part of India is the central and eastern part of the peninsula south of the Satpuras, which is included within the isotherm of 80°, but is below 85°. In April and May, the temperature rises more rapidly in Rájpútána and the Punjab; and, in the second of these months, the greater part of Rájpútána, with Indore, Bhopal, Berar, and the western part of Nágpúr, is surrounded by the isotherm of 95°. Finally, in June, the seat of maximum heat is transferred to the Punjab; where, allowing for elevation, the average temperature of the day is but little below 100°. This phenomenon is repeated, year after year, with apparently unfailing regularity; the only variations being, in the greater or less extent of country included in the isotherms of a given value, and in slight modifications of the form of those lines in different years.

From such records of temperature as we have already at hand, it appears that, in March, the highest average temperature in the peninsula is about the latitude of 20°; and in May between 24° and 26°. Now, in March, the greatest quantity of the solar heat is received on the equator; in April, between latitudes 10° and 15°; and, in May between latitudes 25° and 30°. In the first two months, therefore, the zone of highest temperature (on the land) is in advance (that is, to the north) of the zone of greatest insolation; while, in May, the two zones nearly coincide, the latter being perhaps slightly ahead; and thenceforth, the northward advance of the two zones takes place *pari passu*. The accelerated advance of the zone of temperature in the two earlier months (and indeed, we may add, January and February, since the temperature of the peninsula begins to rise a fortnight or three weeks after the winter

solstice,) is clearly due to the greater thermal receptivity of the land—the greater readiness with which it changes its temperature. The annexed wood-cut, which is a reduction of the *isotherms* chart of India for May 1875, affords an excellent illustration of this difference, and shews that the isotherms or lines of equal temperature at this season, are concentric curves, following almost exactly the contours of the peninsula and of the mountain belt; the highest temperature prevailing in the latitude of 24° or 26°, in the dry region of Ŕájpútána. This character is common to all the hot weather months, and lasts till the setting in of the rains.

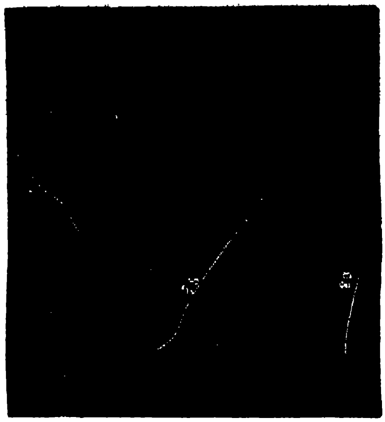

Fig. 2.—Isothermal chart of India in May 1875.

56. Temperature in the rainy season.—As soon as the rains set in, in June and July, the temperature falls over the greater part of the peninsula, more especially in Central India, but it remains high where the rainfall is scanty or wanting; and thus, the Punjab and Sind remain the seat of the highest temperature, until the sun has retreated in declination to the south of the equator.

About the end of September, the loss of heat by the nocturnal cooling of the earth's surface and of the atmosphere resting on it, has so far gained on the antagonistic influence of the diurnal heating, that the temperature of the Punjab begins to fall below that of other parts of India. Meanwhile, the Carnatic has received but little rain during the summer months, and maintains a high temperature, which is further favored by the sun's becoming vertical over this tract during the month of August. In the latter part of October, and in November and December, this region and the eastern part of Ceylon have a higher temperature than any other part of India; and hence the deflection of the south-west monsoon towards these coasts, and the production of the autumn rains of the Carnatic; for we shall presently see that, as a general rule, a high temperature determines a low atmospheric pressure, and the winds tend towards such regions of low pressure in virtue of well-known mechanical laws.

57. Temperature in the cold season.—The fall of temperature at the close of the rains is most rapid in the Punjab. Now, the table of

average cloud proportion, given at the end of this work, shews that the skies of Upper India become comparatively clear of cloud immediately on the cessation of the rains; and that October is the most serene month in the year, (indeed, almost cloudless,) in the Punjab, Rájpútána and Rohilkund. In the lower part of the North-Western Provinces and Behar, October is more cloudy than November, while, in the Lower Provinces and Eastern Bengal, the maximum of serenity or minimum of cloud falls in December. Hence, nocturnal radiation must become a powerful cooling agent in the Punjab earlier than in the Lower Provinces, and this, in conjunction with the more rapid shortening of the days after the equinox, is probably the cause of the more rapid fall of temperature.

During the cold weather months, the temperature depends chiefly on the latitude, that is to say, on the obliquity with which the sun's rays fall on the earth's surface, as already explained in § 54. Hence, as shewn in the accompanying chart for January 1875, the course of the isothermal lines is more or less parallel to the lines of latitude; but less so in the Peninsula than in Northern India; since the distribution of temperature is affected unequally in the former, partly by the course of the cooler currents from the north; partly, it is probable, by differences of radiation, the high dry plateau of Mysore and the hill country of the Western Ghats being cooler than the plains of the Carnatic and the sea that washes the western shores.

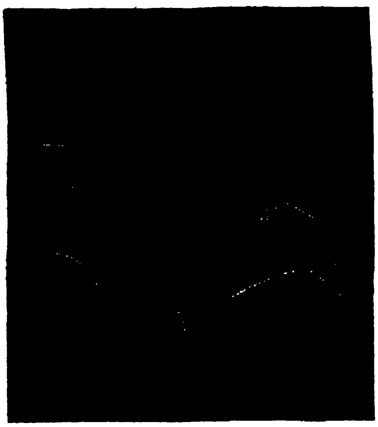

Fig. 8.—Isothermal chart of India in January 1875.

58. Conditions that affect temperature.—On the whole, the temperature of India during the dry season, and that of the drier regions throughout the year, is determined mainly by the direct action of the sun; by the changing equilibrium of the heat gained from direct insolation, and that lost by radiation into space. Of secondary causes affecting the temperature, the most important, by far, are evaporation and obscuration by cloud. Wind direction, regarded as a condition directly influencing temperature, occupies only a third place, except at some parts of the coast line, where the land and sea breezes differ greatly in temperature.

59. Influence of evaporation.—The influence of evaporation, in mitigating the temperature of the sea and the maritime belt of the Peninsula has been already noticed and illustrated. In conjunction with cloud obscuration, it is equally important in the interior of the country, more especially in the rainy season; but the effect of the evaporation of rainfall is, perhaps, most strikingly manifested in the hot season, when a heavy shower is always followed by a day or two of reduced temperature. In July, and, indeed, in a great measure, throughout the rainy season, the course of the isotherms is mainly determined by the quantity of the rainfall and the directions of the rain-bearing winds; the former running more or less at right angles to the latter, and indicating a gradual increase of temperature from the coast line, where, *ceteris paribus*, the rainfall is most copious, to the rainless tract of the Punjab; and in the Peninsula from the west of the east coast.

60. Vertical decrease of temperature.—So far, we have restricted our attention to the variation of the temperature at different seasons and in different parts of the country, as represented by the isotherms of a horizontal plane. We have now to regard the variation of temperature in a vertical direction; that is, at different heights above the sea-level. That the temperature of the air decreases as we ascend above the sea-level, is a fact familiar to most persons—to all, indeed, who have ever climbed an Alpine height, or have paid a visit to one of the hill stations of India; but this decrease is by no means the same at all times of the year; in other words, the temperature of the hills does not vary in the same way and to the same extent as that of the plains at their foot; and the changes to which it is subject are very important, in the light they throw on the great movements of the atmosphere.

61. Causes of vertical decrement.—The causes of the decrease of temperature with elevation are mainly two, and have been explained at length in the preceding chapter. They are, *first*, the dynamic cooling that air undergoes in ascending and expanding, and the dynamic heating, by compression, of descending currents; and *secondly*, the absorption, by the lower strata of air, of the dark heat radiated from the ground, and of that which they receive from the ground by actual contact. It has been shewn in the previous chapter, that an ascending current of dry air, which neither receives nor gives out heat, would lose 1° of temperature in every 183 feet, in virtue of the resistance pushed aside by its expansion; and that, in a current of moist air, so long as it remains unsaturated, and does not deposit cloud, the ratio is not very different; but that

in a cloud, where the air is saturated and continues to deposit moisture on cooling, the rate of cooling, at such temperatures as prevail in India at moderate heights, will not of necessity exceed 1° in 400 feet or 500 feet. A descending current either of cloudless or cloud-laden air will be heated in precisely the corresponding ratios.

62. Conditions of vertical decrement in convection currents. —We might then, perhaps, anticipate that the vertical decrease of temperature would be least rapid in the rains, when a current of saturated air is ascending over the plains of India, condensing much cloud and rain in its ascent; and most rapid in the dry cold season, when the upper strata of the atmosphere are gradually sinking to the surface and flowing away as the beginning of the dry north-east monsoon. But, further, it is one of the conditions of a current ascending by convection, that it should be maintained at a higher temperature than other columns around, which are not ascending; and it is equally essential that a descending convection current should be maintained at a lower temperature than other columns of air around, which are not descending. Now, if we assume the average rate of the vertical decrement of temperature, where there is no convection, to be 1° in 270 feet, (which is about that which results from the table on page 156,) we can see that an ascending convection current of saturated air may be maintained at a higher temperature than the air around, provided it loses no heat otherwise than by its expansion. But that, in order to maintain either an ascending or descending convection current of *dry* air, under these average conditions, the former would require a constant supply of heat from some foreign source, the latter would have to get rid of the heat developed by its compression; since otherwise, that difference of temperature which is the essential condition of the convective movement would speedily be neutralized. Hence, we must draw this final conclusion,—that the maintenance of an ascending convection current over India in the rainy season, and of a descending convection current in the cold dry season, are, in both cases, consistent only with a vertical decrement of temperature less rapid than in regions where no such movement is in progress.

63. Annual variation of vertical decrement in Northern India.—We will test these inferences by comparing the temperatures of stations on the hills at 6,000 or 7,000 feet above the sea, with those of the plains at their foot; selecting, for this purpose, Darjeeling and Goalpara in the damp climate of Sikkim and lower Assam; Chakráta and Roorkee in the drier climate of the North-Western Himálaya and the upper part of the Gangetic plain; and, finally, Murree and Ráwalpindi in the arid climate of the Punjab.

Month	Darjeeling and Goalpara: Difference of temperature.	Darjeeling and Goalpara: Height = 1° Fahr	Chakra'ta and Roorkee: Difference of temperature	Chakra'ta and Roorkee: Height = 1° Fahr	Murree and Ra'walpindi: Difference of temperature	Murree and Ra'walpindi: Height = 1° Fahr
January	21·5	305	16·0	385	9·9	586
February	23·6	278	17·6	350	11·8	493
March	23·2	282	20·3	304	12·6	460
April	20·9	313	20·8	296	14·5	400
May	18·4	356	22·3	276	14·6	399
June	17·1	383	21·6	285	17·5	332
July	17·5	374	19·4	318	19·5	298
August	17·8	368	19·6	314	17·8	326
September	18·4	356	19·9	310	13·8	420
October	20·3	322	17·3	356	10·1	574
November	20·9	313	12·1	509	7·6	705
December	21·2	309	12·5	493	6·6	880
Year	20·1	330	18·3	300	13·0	494

Stations	Elevation in feet.	* Difference
Darjeeling	6,941	6,555
Goalpara	386	
Chakrata	7,051	6,165
Roorkee	886	
Murree	7,467	5,817
Rawalpindi	1,650	

The greater the difference of temperature in any month, as shewn by this table, the more rapid is of course the mean vertical decrement of temperature between the pair of stations compared, and *vice versâ*. On comparing the figures in one and the same column, and then the general results, we see that the range of variation is less at Darjeeling than at Chakráta, less at Chakráta than at Murree; and that, whereas in the damp Bengal atmosphere, the greatest difference of temperature between the hills and the plains is in February and the least in June; in the North-Western Provinces the greatest is in May, the least in November; and in the dry atmosphere of the Punjab, the greatest is in July, the least in December.

The mutual relations of the variations, in the three contrasted cases, will become most apparent, if we throw the data into the form of a diagram, as in the annexed woodcut. The simplest curve is that of Murree, which has a maximum increment of elevation for 1° in December, a minimum in July. The table shews that, in the former month, the average temperature at Murree, nearly 6,000 feet above Ráwalpindi, is only about 6½ degrees lower than at the latter station; while, in July, the difference is not less than 19½ degrees, or exactly three times as great. Now, January is the coldest month and June the hottest and driest; and the ground being the chief radiator of heat at the former season, and the

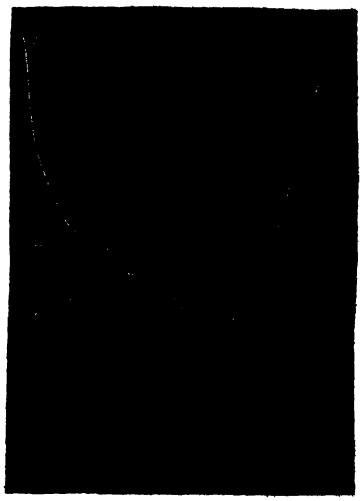

Fig. 4.—Increments of elevation corresponding to a decrement of 1° Fahr. 1.—Murree. 2.—Chakráta. 3.—Darjeeling

chief absorber at the latter, the lowest stratum of the atmosphere in contact with it tends to acquire the same temperature; therefore, approaching that of the more elevated station in the cold season, and departing more widely from it at the hot season. This is precisely the same variation that has been found to obtain between day and night, and between summer and winter, by Mr. Glaisher in England, by Plantamour and Kaemtz in Switzerland, by Mohn in Norway, and by Rundell and Hillman in North America. Indeed, it occasionally happens in the winter time during the day, and constantly at night, that the normal temperature variation is reversed in the lowest strata of the atmosphere; the air being actually colder near the ground than at certain moderate elevations. Such is especially the case in regions of great cold and high atmospheric pressure,—regions where the air is calm, but from which cold winds blow outwards in all directions; and these tracts of the atmosphere are termed anti-cyclonic, being in all their essential conditions the reverse of cyclones.[1] It is very probable that this will be found to be the case also in the Punjab, when comparative observations shall be made at different heights above the ground surface; in any case, it is a centre from which the surface winds radiate out in the winter; and, as will be seen in the next section, it is included in the region of highest average pressure at that season. So far, then, the vertical variation of temperature in the Punjab, in the winter, coincides with that indicated by theory and by observation in other parts of the world, as that required for the maintenance of a descending convection current. Between Chakráta and Roorkee, the difference of temperature is also at its minimum in November and December; but it is almost twice as great as between Murree and Ráwalpindi; while, between Darjeeling and Goalpara, the ratio of difference is three times as great; and although it increases in the subsequent months, it is no longer the annual minimum. The inference that we should draw, therefore, from these facts is that, in the Punjab, the descent and outflow of air in the winter months is greater than in the North-Western Provinces, and in these latter greater than in Bengal. And it is very probable that such is really the case, although the available records of the movement of the wind are insufficient to enable us to bring it to the test.[2]

[1] The term cyclone is in popular language restricted to storms of destructive violence, but all vertical movements of the wind around a region of minimum pressure, may, with propriety, be designated by the same term. *See* § 75.

[2] The required test of this conclusion lies of course in the answer to the question—Does the average movement of the wind increase in direct proportion to the area of the country from which it is blowing, or less rapidly? By the average movement of the wind must here be understood the whole quantity of air that passes across a given line, in the normal direction, in the unit of time; and as this determination demands a knowledge of the depth and mean velocity of the current and not merely of its surface velocity, it is one which we have no means of arriving at at present.

On the other hand, when the south-west monsoon is at its height, say in July, the mutual relations of the three pairs of stations are reversed, the difference between them being, however, much less than at the opposite season. The least difference of temperature, indicating the slowest vertical decrement, is shewn by the Bengal stations; next in order come those representing the North-Western Provinces; and the greatest difference, indicating the most rapid decrement, is exhibited by those of the Punjab. Now, this is also the order of the three regions in point of cloudiness and copiousness of rainfall; and we may conclude with much probability that the relative activity of the ascending currents in these three regions also follows the same order of decrement.

64. Contrasted energy of cyclones and anti-cyclones.—Except in Bengal, then, the vertical decrement of temperature is much slower in the winter months than in those of the rains; slower with the descending than with the ascending air current, with an outflow from a region of maximum than with an inflow to one of minimum pressure; and this, notwithstanding that the movement of the wind is considerably more rapid at the latter than at the former period. This last fact, *viz.*, the inferior velocity of the winds around anti-cyclonic, as compared with that around cyclonic centres, appears to be an universal law,[1] and the probable explanation is very obvious. In a descending current, *work is done on* the air, which is gradually compressed; and the heat, generated dynamically by the compression, must be got rid of; whereas, to maintain an ascending current, which is *doing work against* the superincumbent atmosphere, heat must be supplied. The former is necessarily a slow process, because it is purely local, and depends on the local radiation. But the latter is not necessarily local. As the latent heat of water vapour, the requisite energy may be brought from a distance, and merely set free as heat in the heart of the ascending current; and such is the case to a vast extent during the rainy season in India. A further distinction between the two cases, which goes some way to explain the more uniform mean vertical distribution of temperature in the cold season of the Punjab, is this,—the cooling of the lowest stratum of the air is mainly effected by the radiation from the ground, and the reduction of the atmospheric temperature is to a great extent a secondary process. Hence, the ground temperature approximates nearly to that

[1] A consequence of this fact is, that anti-cyclonic areas must be, on the whole, more extensive than cyclonic areas; for since, in the long run, the quantity of air that ascends must be equal to the quantity that descends, the momentum of both classes of currents must be equal, and the increased velocity of the one must be compensated by the increased sectional area of the other; and this inference is confirmed by observation. But the energy of ascending currents is greater than that of descending currents in the proportion of their relative velocities.

at an elevation of 3,000 or 4,000 feet. But in the rains, latent heat is set free only in the cloud stratum, which is normally at a height of 3,000 feet and upwards; and in the cloudless atmosphere below, the decrement of temperature will be much more rapid than in this stratum, for the reasons shewn in the previous chapter.[1] The actual variation of the temperature decrement, at different seasons of the year and different hours of the day, is an inquiry of great interest in this connection; and is one in which residents on the hill slopes, such as tea and coffee planters, might render valuable assistance.

65. Vertical decrement of temperature in the Peninsula and Ceylon.—Before leaving this part of the subject, I give, for comparison with the above, a table shewing the annual variation of the temperature decrement between Pachmarhi and Hoshangabad in the Central Provinces; and between Nuwera Eliya on the mountains of Ceylon, and Colombo and Batticaloa on the west and east coasts respectively. These may be taken as representing the state of the atmosphere at places where there is but little vertical movement of the atmosphere either upwards or downwards; such is especially the case between Pachmarhi and Hoshangabad. Between Nuwera Eliya and Colombo, such a movement does take place, to some extent, in the summer months; but here it is such as is produced by an obstacle in the way of a horizontal current rather than by convection.

Month.	Pachmarhi and Hoshangabad.		Nuwera Eliya and Batticaloa.		Nuwera Eliya and Colombo.	
	Difference of temperature.	Height =1° Fahr.	Difference of temperature.	Height =1° Fahr.	Difference of temperature.	Height =1° Fahr.
January ...	9·1	273	20·0	306	21·6	283
February ...	8·8	282	20·7	296	22·2	275
March ...	8·6	289	21·1	290	21·7	281
April ...	8·9	279	22·9	268	22·4	273
May ...	9·7	256	23·5	261	22·1	276
June ...	10·8	230	26·0	236	22·1	276
July ...	9·4	264	27·1	226	22·9	267
August ...	9·3	267	25·3	242	22·4	273
September ...	9·2	270	24·3	252	22·1	276
October ...	10·4	239	23·2	264	21·7	281
November ...	11·2	224	20·6	297	21·1	289
December ...	9·2	270	20·8	296	22·4	273
Year ...	...	262	...	269	...	277

Stations.	Elevation in feet.	Difference.
Pachmarhi ...	3,504	2,484
Hoshangabad ...	1,020	
Nuwera Eliya ...	6,150	6,129
Batticaloa ...	21	
Nuwera Eliya ...	6,150	6,108
Colombo ...	42	

[1] This conclusion from theory is fully confirmed by the observations of Mr. Welsh (Phil. Trans., 1853, p. 311) and Mr. Glaisher (Brit. Assoc. Report, 1866) in their balloon ascents.

In all cases in the foregoing table, the range of variation is smaller than in the least variable of the Himálayan pairs of stations, and the mean increment of elevation is less.[1] So far, then, the conclusion from theory is borne out by observation; *viz.*, that the vertical decrement of temperature is slower where ascending and descending convection currents prevail, than where such currents are rare and exceptional.

66. Comparative temperatures of hill sanitaria.—Some conclusions, bearing on the climate of hill stations, may be drawn from the data above given, which are not without interest. The hills of the Peninsula afford, for equal elevations, a greater reduction of temperature than do the Himálayan stations; and the advantage thus gained varies less with the season of the year. The summer temperature of the Himálayan stations, at about the same elevation, is apparently the higher, the further the station lies to the north-west; but the winter temperature is very nearly the same in all parts of the chain; and such places as Murree, Chakráta, and Darjeeling are far from exhibiting, at that season, those marked differences which characterize the plains of the Punjab and Bengal. The foregoing discussion of the variations of air temperature, with varying elevations above sea-level, has reference only to hill stations; that is, to cases in which the elevation is gained by a tolerably abrupt rise from the general surface. On the plateaux of the interior, the temperature is doubtless lower than it would be at the sea-level under otherwise similar circumstances; but the reduction of temperature gained by the elevation is less than in the case of hill stations; since the heat radiated from the ground is relatively much more copious. It is difficult to obtain data for a satisfactory determination of the effect of difference of level under these circumstances; since there are no satisfactory means

[1] The following results of Mr. Glaisher's balloon ascents in 1862—64, from the British Association Reports in 1864, shew that, in England, which is also a region where the air has a prevalent horizontal rather than a vertical movement, the average vertical decrement of temperatures is comparable with that of Central India and Ceylon.

Average increment of elevation corresponding to a fall of 1° Fahr.,—

			Sky cloudy.	Sky clear.
0 to 1,000 feet	...	...	223 feet	162 feet
„ „ 2,000 „	...	...	247 „	184 „
„ „ 3,000 „	...	...	255 „	204 „
„ „ 4,000 „	...	...	263 „	223 „
„ „ 5,000 „	...	...	271 „	239 „
„ „ 6,000 „	...	...	277 „	256 „
„ „ 7,000 „	...	...	287 „	271 „
„ „ 8,000 „	...	...	299 „	279 „
„ „ 9,000 „	...	...	311 „	289 „
„ „ 10,000 „	...	...	321 „	298 „

of eliminating the effects of other geographical differences, such as the slope of the ground, the nature of the soil, the distance from the sea, &c. Comparing Házáribágh at 2,010 feet, with Berhampore at 65 feet, and Gya at 347 feet, the difference of temperature, on the mean of the twelve months and on the average of the two stations, is equivalent to a reduction of 1° in 504 feet; and Seoni at 2,030 feet, compared in like manner with Nagpur at 1,025 feet and Jubbulpore at 1,351 feet, gives a reduction of 1 for 394 feet. In general, the difference is less in the winter than in the summer months.

67. Annual and diurnal range of temperature.—The range of temperature, both in the annual and diurnal period, varies very greatly in different parts of India. In both respects, the Punjab is the seat of the greatest variation; and Ceylon and the Andaman and Nicobar Islands, that of the least range. It would appear from the existing registers of temperature in the Punjab, that the absolute annual range at such stations as Dera Ismail Khan, Mooltan, Rávalpindi, Sialkot, Lahore, and Ludhiana is between 90° and 100°, sometimes even exceeding the latter; on the other hand, at Galle, on the south-west coast of Ceylon, the difference between the highest and lowest temperatures recorded during the year 1875 was only 16·2°, and that at Nancowry 20·9.°

The average diurnal range at the Punjab stations above-mentioned is about 30° on the mean of the year, and in April 40°; in the Central Provinces (Nágpur, Jubbulpore, Raipur, Sambalpur, &c.,) between 20° and 25° on the mean of the year, and in March from 30° to 35°; while, at Galle, the annual average is only 6½° and the greatest monthly average not 9.°

68. Cyclical variation of solar radiation.—It was remarked at the close of the preceding chapter, that the solar radiation, which is the source of all atmospheric energy, is apparently subject to variation, and that the activity of the meteorological changes of our atmosphere must therefore vary in a like manner. Sir W. Herschell, at the beginning of the present century, attempted to shew, from the very imperfect records at his command, that "years of remarkably abundant or deficient spots have been also remarked for their high or low general temperature, and especially for abundant and deficient harvests." During the last ten years, much attention has been given to this subject; and a certain periodicity, corresponding to that of the abundance of sun-spots, has been traced out in several kinds of meteorological phenomena.

It is now well known, from the researches of Hofrath Schwabe of Dessau, Professor Wolf of Berne, and more recently of Carrington,

Balfour Stewart and Loewy, that the abundance of the spots on the sun's face undergoes a periodical increase and decrease in a cycle of about 11·11 years. In addition to, and superimposed on this, the Wolfian period, are other variations of longer period; but the law of these is less accurately known. Sun-spots, as we know now from the observations of Chacornac and Lockyer,[1] are not, as was at one time supposed, cooled solid masses or even clouds floating on the solar surface, but rather gaseous maelströms in the luminous envelope, the photosphere, caused by the descent of streams of the external cooled atmosphere into the body of the sun. They indicate, therefore, increased activity in the movements of the solar atmosphere and a withdrawal of a portion of the cooled and absorbing envelope; and, as might be anticipated, the recent discussion of observations of radiation temperatures by Mr. Baxendall of Manchester, and also, in India, by the author of this work,[2] have gone to confirm the original idea of Sir W. Herschell, and to shew that the solar radiation is greatest in years of abundant sun-spots and *vice versâ*. What is the amount of its variation is not yet known, and can be ascertained only by long-continued observations with the actinometer; such as I trust may one day be undertaken in India.[3] The results of 11 stations, in different parts of India, shewed an increase of at least 6° in the mean equilibrium temperature of solar radiation at the earth's surface, between 1868 and 1871, (the last following a year of maximum sun-spots;) and this, I am inclined to think, is in defect of the truth. The variation is thus by no means inconsiderable.

69. Cyclical variation of air temperature.—It seems at first sight parodoxical, that the discussion of the air temperature by Gautier, and more recently by Professor Köppen, shews a variation in the opposite direction to that of the intensity of solar radiation. The latter physicist finds that, in the tropics, the maximum air temperature coincides more nearly with the minimum than with the maximum of sun-spots; preceding the former, however, by one to one and a half years. As a possible solution of this parodox, I have put forward the following considerations:— "The temperatures dealt with by Professor Köppen are, of course, those

[1] For further reference, see Lockyer's Solar Physics, page 70.

[2] Nature, Vol. XII, pages 147 and 188: Journal, Asiatic Society of Bengal, Vol. XLIV, Part II, page 21; Zeitschr. Oesterr. Met. Gesell., Vol. X, page 261.

[3] There appeared at one time to be a prospect of an observatory for the special purpose of sun observations being established in the Himálaya; and certainly few parts of the world possess such advantages for this purpose as the drier portions of the range which borders the Punjab province. To the regret of all who can appreciate the importance of the subject, this scheme has not been carried out; but I venture to express a hope that it may yet be revived and under happier auspices.

of the lowest stratum of the atmosphere as observed at land stations; and must be determined, not by the quantity of heat that falls on the exterior of the planet, but on that which penetrates to the earth's surface, chiefly the land surface of the globe. The greater part of the earth's surface being, however, one of water, the principal immediate effect of the increased heat must be to increase the evaporation; and therefore, as a subsequent process, the cloud and the rainfall. Now, a cloudy atmosphere intercepts a great part of the solar heat; and the re-evaporation of the fallen rain lowers the temperature of the surface from which it evaporates, and that of the stratum of air in contact with it. The heat liberated by cloud condensation doubtless raises the temperature of the air at the altitude of the cloudy stratum, but this is not recorded in our registers. As a consequence, an increased formation of vapour, and therefore of rain, following on an increase of radiation, might be expected to coincide with a low air-temperature on the surface of the land."

70. Cyclical variation of rainfall.—The above speculation has been in part suggested by the discovery of Messrs. Meldrum and Lockyer, that the frequency and energy of cyclones and the rainfall of the globe appear to vary directly as the abundance of sun-spots. In respect of cyclones, Mr. Meldrum finds that, not only their number, but also their area and dimensions shew a very marked periodicity, with maximum and minimum epochs corresponding to those sun-spots. The evidence afforded by rainfall registers, as might be expected in the case of so variable an element, is more conflicting; but Australia, North America, the South Pacific, and, to a certain extent, Europe and India, appear to afford confirmation of the hypothesis, to a degree which cannot be attributed to fortuitous coincidence.

In my own opinion, however, the evident periodicity of cyclone intensity is more conclusive of the increased evaporation of maximum sun-spot years, than the recorded rainfall at land stations; holding, as I do, the view elaborated by Reye, that the immediate source of the energy of cyclones is the condensation of vapour over the cyclone. I will defer the discussion of this point, as well as the further notice of the rainfall variation, to its proper place in a subsequent part of this work.

71. Secular variation of solar radiation.—The facts recounted in § 68 afford evidence that, to a certain small extent, our sun must take rank among the variable stars. It is true that, viewed from the distance of even the nearest of the (so-called) fixed stars, such small variations as have been recorded during the last two centuries would be absolutely inappreciable. But greater degrees of obscuration are

recorded in past times, as, *e. g.*, in the year A. D. 536, when the sun is said to have suffered a great diminution of light, which continued fourteen months; and in those remote epochs which geology deals with, there are evidences of such vicissitudes of climate as seem inexplicable on any other hypothesis than that of a great variation of the solar heat. Such, for instance, is the occurrence of remains of a warm temperate flora of the Miocene epoch in the now ice-bound rocks of Greenland: and, on the other hand, the abundant evidence of glaciers down to low levels in the Himálaya and the Patkoi Hills of Assam, in times which are certainly pre-historic, but not, perhaps, anterior to the existence of man. Such cases as these, and of extensive accumulations of ice-borne boulders in latter palæozoic times in south Africa and in India, far down in the tropical zone, can hardly be explained by the ingenious theory of Mr. Croll; and seem to point to an amount of variation in the solar heat, both in excess and defect of its present intensity, that would entitle our sun to a place among the more variable of the stars.

ATMOSPHERIC PRESSURE AND WINDS.

72. Relations of wind and pressure.—It follows from elementary mechanical laws, that the movements of the atmosphere and the pressure of its different parts, bear to each other an alternative relation of cause and effect. Any difference of pressures in the same horizontal stratum of the atmosphere *tends* to set a current in motion from the place of the higher to that of the lower pressure, and so long as such difference of pressure is maintained, the movement of the air will be accelerated until the resistances arising from friction, the renewal of momentum, &c., exactly counterbalance the effective difference of pressures; when the motion becomes uniform. On the other hand, whenever a current of air meets with an obstacle, as, for instance, a cliff or a building, the pressure is raised where the motion is checked; and the low pressure which exists in the centre of a cyclone is owing, in part at least, to the circulation of the winds around.[1] But although we must not ignore the fact that pressure, as measured by the barometer, is to some extent affected by the movements of the winds, such cases are of quite subordinate importance in the general scheme of meteorological action; and we may class them with friction, as representing a portion of the resistance to be overcome when the air is set in motion by those more influential differences of local pressure which are produced by heating, evaporation, and their opposites.

Before proceeding further, I must premise one or two definitions.

73. Isobaric planes and baric gradients.—I have remarked above that any difference of pressures, in the same horizontal plane[2] of the atmosphere, tends to produce an air current from the seat of higher to that of lower pressure. The distribution of pressures in any given horizontal plane may vary indefinitely, and, as we shall presently see, may be very different at different levels; so that, a region of relatively low pressure in the lower part of the atmosphere may coincide with one of relatively high pressure in the higher strata; and *vice versâ*. But since, in every vertical column of the atmosphere, the pressure decreases as we ascend and increases as we descend, we may always imagine the atmosphere to be divided into layers, by a series of more or less undulating or inclined planes, each of which shall have an equal pressure throughout.

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[1] On this point see more especially Dr. J. Hann: Zeitschr. Oest. Met. Gesell., Vol. X, No. 6, also *postea* § 143.

[2] By this term is here to be understood the surface of equilibrium of a fluid under the influence of gravity and the earth's rotation.

One such plane, for instance, may traverse all those levels, where there is a barometric pressure of 29 inches; another one of 28 inches, and so on; and this conception will much facilitate our further inquiries. I shall speak of these as *isobaric planes* or planes of equal pressure; and as their several parts are variously inclined to a horizontal or water-level surface, I shall speak of the slope of any such part as a *baric gradient*. In a diagram, such as the accompanying figure, we must represent these several planes in section, by lines. Let the line AC represent the section of a horizontal plane, and the dotted line AB that of an isobaric plane inclined to it. Then the angle CAB represents the baric gradient. In the horizontal plane AC, the pressure at A is higher than at C; and an effective force, equal to this difference of pressure, tends to produce a motion of the air from A to C. In comparing gradients, it is convenient to suppose B C to represent a constant difference of pressure, *e. g.*, one inch or 0·1 inch, and to express the gradient, as engineers do, by the distance A C which corresponds to that fall or rise of pressures; or we may adopt the converse method, and express the gradient by the barometric difference corresponding to a constant distance, such as 100 miles. This is the method adopted by most English meteorologists. Thus, we may say that, in the south-west monsoon, the mean barometric gradient over the Bay of Bengal is one-tenth of an inch in 400 miles, or 0·025 inch in 100 miles; and that, in cyclones, the gradients, near the centre of the storm, sometimes amount to 1 inch in 50 miles, or 2 inches in 100 miles.

Fig. 5.—The baric gradient.

74. Isobaric lines or isobars.—*Isobars* are the lines, along which, the successive isobaric planes intersect one and the same horizontal plane. They are, therefore, lines of equal pressure on a horizontal plane. As laid down on charts, they generally shew the pressures at the sea-level; or the hypothetical equivalent, at that level, of the pressures actually observed.

75. Cyclones and anti-cyclones.—The term *cyclone*, although, in popular language, its use is restricted to the case of violent revolving storms, is sometimes, and justly, applied to cases, where the winds circulate around an area of relatively low pressure, without attaining to any very high velocity. In all cyclones, this motion is not circular, but spiral and vortical. The currents circulate around the seat of the greatest depression, while drawing in towards it. On the other hand, around a region of relatively high pressure, the winds blow spirally

outwards; constituting, what Mr. Galton has termed, an *anti-cyclone.* Thus, winds do not blow in a direct course from a place of high to one of low pressure; but, on the contrary, very obliquely. In a cyclone, or around a region of low pressure in the Northern Hemisphere, the direction of the circular motion is left-handed, or in the direction opposite to that of the clock hands: while in an anti-cyclone, or around a region of high pressure, the circulation is right-handed or coincident with that of the clock-hands. The accompanying diagram represents a cyclone A and anti-cyclone B, and the course of the winds between them; the closed lines represent the isobars of successive increments of pressure, and the arrows the course of the winds in the Northern Hemisphere. In the Southern Hemisphere, the direction of the circulation is reversed, cyclones being all right-handed spirals, while ati-cyclones are left-handed.

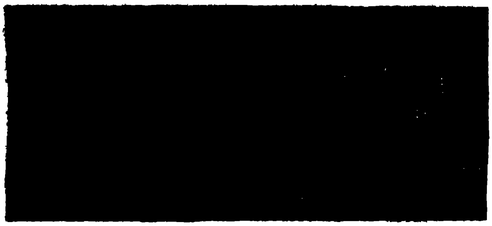


Fig. 6.—Isobaric chart of cyclone and anti-cyclone.

76. Ferrel's law.—This deviation of the winds from the radial direction is, as Ferrel has shewn, a consequence of the earth's rotation. In general terms, any mass of matter whatever, moving in a rectilinear path towards any point of the compass, on the earth's surface, tends to deviate to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere. When the velocity of the movement is expressed in miles per hour, the deflecting force is given in round numbers by the formula $\frac{v \cos. \theta}{150,000} g$, wherein v is the velocity of the movement, θ the angle of polar distance, and g the force of gravity. The force, therefore, decreases as the sine of the latitude, becoming 0 at the equator; a fact, which explains why cyclones are unknown within a few degrees of the equator, and also the comparative slowness of their formation in tropical seas. In obedience to the above law, any set of wind-currents, radiating from a centre, curve to the right and tend to revolve in the direction of the clock-hands in the Northern Hemisphere; while any set of currents converging to a common centre, also diverge to the right and tend to become centrifugal; but this tendency being resisted by the influence of the pressure gradient, they revolve with a left-handed curvature.

Ferrel's law, it is to be observed, is perfectly general. It applies to any mass of matter whatever, whether solid, liquid, or gaseous, moving in any azimuth, on the surface of a revolving sphere or spheroid. Railway trains and steamers, rivers and marine currents, and winds of all kinds,

equally obey the tendency to deviate to the right in the Northern, and to the left in the Southern Hemisphere; and this tendency increases in the same ratio as the velocity of their motion, and as the sine of the latitude of the place.

77. Dove's and Buys Ballot's laws.—The law of the wind's rotation, which was recorded as a fact of observation by Lord Bacon, and received its first partial explanation at the hands of the veteran meteorologist of Berlin; and the law of Buys Ballot, which expresses the probable direction of the wind as a consequence of the observed relations of pressure, are both particular consequences of Ferrel's law. The first expresses the tendency of a wind in the Northern Hemisphere to *veer*, or to change in direction with the hands of the clock; if a north-west wind, for instance, to become easterly; if a south-east wind, to change through south to south-west and west; and in the Southern Hemisphere to follow an opposite course. Dove's explanation of this tendency relates only to winds from northerly or southerly quarters, and is given in words[1] of which the following is a translation :—

"The velocity of the rotation of any given point on the earth's surface varies as the diameter of the parallel circle of latitude on which it lies; it increases from the pole, where it is 0, to the equator, where it is greatest. When apparently at rest, the air has the same velocity of rotation as that part of the earth's surface on which it reposes." Omitting the next passage, which is erroneous, in excluding from the law the case of east and west winds, he proceeds : "When the air from any cause is impelled from the poles towards the equator, it comes from places which have a low velocity of rotation to those where it is greater. The air, therefore, is moving eastward with a less velocity than the places over which it passes, and seems to flow in the opposite direction, *viz.*, from east to west. The deviation of the wind from the original direction will be the greater, the greater the difference between the respective velocities of rotation of the place of the wind's origin and that where it is observed, *i. e.*, the greater the difference of their latitudes."

This tendency of the wind to *veer* is less striking in India than in higher latitudes; and for the very obvious reason that, not only is the sine of the latitude, (which is one of the determining magnitudes,) much lower, but also, as a general rule, the velocity of the wind (another factor) is likewise low. But the law still holds good. A discussion of the anemometric registers of Calcutta for fifteen months[2] shew that, while the wind vane had made nine complete revolutions in the direction north,

[1] Meteorologische Untersuchungen, 1832, page 125.
[2] Indian Meteorological Memoirs, Vol. 1, p. 8.

west, south, east, north, it made thirty-four in the opposite, *i. e.*, the normal direction.

Buys Ballot's law extends to all winds, those relations between pressure and wind direction that we have already seen illustrated in cyclones and anti-cyclones. It will be seen on a glance at the diagram, fig. 6, that, in all cases, if we suppose ourselves looking in the same direction as that in which the wind is blowing, the lower pressure is on our left and a little in front, the higher on our right and a little behind. Buys Ballot's law expresses the fact that, if a line be drawn between the seats of highest and lowest pressure, the direction of the wind approaching this line, will form an angle of 60° or 80° with it; the obtuse angle being on the side of the lowest pressure.

78. **Land and sea breezes.**—The principal cause of those variations of local pressure that determine the course of the winds, are the variations of temperature that have been described in the preceding pages. We have seen, in the introductory chapter on the physical laws of the atmosphere, [§ 5] that the immediate effect of a rising temperature on a mass of confined air, is to raise its pressure; but that, if the air be unconfined, (and this is the case with the atmosphere resting on the earth's surface,) the increased tension is speedily relieved by expansion; and the heated air becomes less dense, while its pressure is brought into equilibrium with that of the surrounding atmosphere. The ulterior consequences will vary according to the part of the atmosphere that is heated: Every case of expansion must of course produce some movement in the air around; and it is usually assumed that this movement consists simply in a lifting of the superincumbent atmosphere, somewhat as the piston of an air-engine is lifted by the expansion of the heated air beneath it. That such is the exclusive result is, I think, open to question, and I shall presently have occasion to revert to the discussion of this point; but it is undoubtedly the *chief* movement directly set up; and before proceeding further, we will turn our attention to one or two of the more immediate consequences of this action. Let A B in the annexed diagram represent a land surface, and B C a sea surface contiguous to it. We have learned in §§ 22, 29, that the same amount of solar heat being expended on both, the air over A B if simply heated will have its tension raised more than seven times as much as that over B C by the simple evaporation of water; and the actual results will be largely influenced by this difference. The effect, in both cases, being chiefly restricted to the

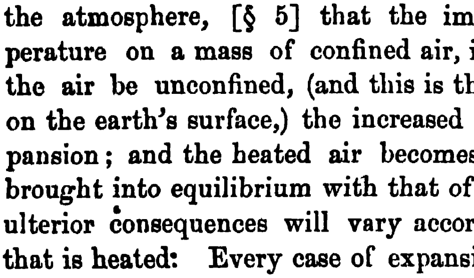


Fig. 7.—Diagram illustrating the cause of sea breezes.

lowest strata of the air, this increased tension will be relieved, as above stated, by expansion, and the lifting of the superincumbent mass, somewhat in the proportions deduced in § 29. Now, if, before being heated, the atmosphere of the whole area is in a state of equilibrium, so that the horizontal lines *de*, *fg*, &c., represent planes of equal pressure, the result of the above process will be, that these isobaric planes will assume the form indicated by *d'e'*, and *f'g'*. A gradient will be produced, with a head of pressure over the land at the levels *d'* and *f'*; and, at these levels, a current of air will flow outwards towards *e'* and *g'*. By this process, a quantity of air will be removed from the atmosphere over A and will accumulate over C; and, at the level of the land and sea-surface, the *static pressure* or weight of the column at C will become greater than that at A. A lower current of air will then set from C to A, and will be felt as a sea breeze. At night, the conditions will be reversed. The cooling and contraction of the air over A B will depress the planes of equal pressure and give rise to a head of pressure over C, and an upper current will flow from *g* to *f* and *e* to *d*, while a lower current will blow from A to C. Such is the probable explanation of the daily land and sea breezes, which are felt on all or nearly all parts of the coast of India and other tropical countries, except when the monsoons are at their height; and even then, if not blowing directly at right angles to the coast, the wind frequently varies through a point or two, tending towards the land in the afternoon, away from it in the early morning.[1]

79. Mountain winds.—Another effect of the diurnal heating of the land, familiar to travellers on the high plains of Rupshu, the Lingzhithang, &c., and the high passes of the Himálaya and the Kárakoram, is the violent cold wind which blows daily during the afternoon hours in these regions, subsiding only at sunset; and, on the other hand, in the cold morning winds, which blow down the great drainage valleys of the Himálaya, and are more especially felt where they debouch on the plains. The cause of the former of these is explained in the annexed diagram.[2] Let AB be a portion of the plains or even a broad enclosed valley like that of the Indus in Ladák, and BC a portion of the mountain mass that dominates it. The diurnal range of temperature, on

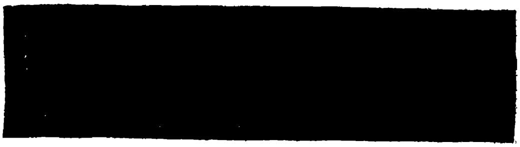


Fig. 8.—Diagram illustrating the cause of afternoon winds on high mountain plains.

[1] We shall have occasion to verify this explanation in respect of the diurnal oscillations of pressure at the sea-surface, in treating of the diurnal oscillations of the barometer in § 97.

[2] The explanation here given, of mountain winds, is identical with that given by General Strachey. See, *e. g.*, Proc. As. Soc., Bengal, 1871, p. 16.

the plains, appears to be about one-half greater than on the mountains, at the elevation of 7,000 or 8,000 feet; and the range further diminishes with greater elevations. Hence, one consequence of the diurnal heating of the air must be a disturbance of the planes of equal pressure, as shewn by $d'e'$, $f'g'$ in the figure; and a day wind will blow upwards towards the centre of the mountain mass, which is doubtless that experienced and so often described by travellers in these high regions. That the atmosphere of the plains is thus lifted, seems to receive confirmation from the fact that, the diurnal fall of pressure between 10 A.M. and 4 P.M. (a subject presently to be discussed) is less at such hill stations as Simla, Darjeeling, &c., which immediately overlook the plains, than on the plains themselves, and less than the fall during the night; so that there would seem to be a higher average pressure over these stations in the afternoon and evening, than in the early morning; which excess Plantamour explained, by the lifting of the atmosphere *en masse*, and the elevation of a larger proportion above the level of the hill tops. The compensating current that, during the night, restores over the plains the equilibrium which has been disturbed in the day-time by the action above described, if not restricted to the valleys, is, at all events, not felt on the higher plains of Thibet.

80. Convection currents.—The disturbance of the equilibrium of pressure described in § 78 as giving rise to land and sea breezes, is a simple illustration of that which characterizes convection currents in general. The complete scheme of pressures and the resulting currents is shewn in the annexed diagram, where A B, C D, E F, represent planes of equal pressure, of which E F alone conforms to a condition of horizontal equilibrium, and may be termed the *neutral plane*. The plane AB represents a head of a pressure at B, and CD a head of pressure at C, which derangement of equilibrium must give rise to currents from C to D and from B to A. In order to complete the circulation such as is here represented, there must, of course, be an ascending current at A, and a descending current at B. Moreover, since the pressure at C is the same as at D, and that at A the same as at B, the difference of pressure between C and A and between D and B must be equal; and, neglecting that small increase of pressure at B, which is produced dynamically by the descending current, and that small decrease at A due to the ascent of the air over it, the column of air D B must have the same weight as the loftier column AC; the mean density of the

Fig. 9.—Diagram illustrating the cause of convection winds.

air in each case being inversely as the height of the column. In order to maintain this difference of density, there must be a constant abstraction of heat between C and D, and a constant absorption of heat between B and A, in addition to that loss of heat in the sinking column DB, and that absorption of heat (or evolution of latent heat) in the ascending column AC, which we have already seen to be conditions of the maintenance of such currents.

81. The Indian monsoons.—The state of things described in the preceding paragraph and represented in the diagram, figure 9, is essentially that of the Indian monsoons. In the winter, during the prevalence of the so called north-east monsoon, DB will represent the descending air column in the Upper Punjab, and also in the tracts of high pressure in Central India, Upper Assam, &c.; and indeed more or less over the whole of Northern India. From these tracts, the surface wind-currents flow away to the southward, but always with more or less tendency to an anti-cyclonic circulation. On the other hand, during the rains, when the south-west monsoon is at its height, AC will represent the ascending column over Northern India, where the winds become more or less cyclonic; as may be verified on consulting the charts of those months, published in the Annual Report of the Meteorological Department. At the former season, the Upper Punjab is, in general, the seat of the highest pressure and the lowest temperature. In the rains, it is that of the lowest pressure and the highest temperature.

82. Variations in the mean density of the lower atmosphere.—A comparison of the temperatures and pressures at the different hill stations, taken in conjunction with those of neighbouring stations on the plains below, afford a fair, if not absolutely accurate criterion of the respective mean temperatures and densities of the lower 7,000 feet of the atmosphere, at opposite seasons, and in different parts of the country and thus enable us to verify the foregoing observations.

The following table exhibits the mean temperature and barometric weight of a column of air 7,000 feet in height above the sea-level, in different parts of India, in each month of the year, as computed from the above data; the temperatures being calculated on the assumption, that the mean vertical decrements of temperature given in the tables at pages 153 and 156 hold good throughout. From the observed pressures of the hill stations and the plains, have been computed those at 7,000 feet and sea-level respectively; and the differences of these latter pressures are taken as the barometric weight of the column in each case. Neglecting the variation of gravity, which is very small, the mean densities are, of course, as these barometric weights.

Computed mean temperature and barometric weight of air column between sea-level and 7,000 feet.

Months.	Darjeeling and Goalpára.		Chakráta and Roorkee.		Murree and Ráwalpindi.		Nuwera Eliya and Colombo.	
	Mean temp.	Baro. weight.	Mean temp.	Baro. weight.	Mean temp.	Baro. weight.	Mean temp.	Baro. weight.
	deg.	ins.	deg.	ins.	deg.	ins.	deg.	ins.
January	52·7	6·697	50·1	?	47·8	?	67·7	6·557
February	56·5	6·638	54·3	?	526	?	68·3	6·550
March	62·3	6·553	62·2	?	61·2	?	69 8	6·529
April	67·2	6·449	73·0	?	71·7	?	70·6	6 506
May	69·6	6·413	78·8	?	80·0	?	71·1	6·505
June	71·8	6·381	80·4	?	87·7	?	69·1	6·528
July	73·1	6 365	76·2	?	83·4	?	68·8	6·554
August	72·9	6·386	75·5	?	81·7	?	68·5	6·556
September ...	71·7	6·417	74·0	?	79·1	?	68·5	6·562
October	68·3	6·470	68·2	?	71·4	?	68·6	6·559
November	61·3	6·582	59·4	?	59·2	?	68·6	6·538
December... ...	55·3	6·654	52·6	?	51·6	?	68·0	6·560
Year ...	65·3	6·502	67·2	?	69·0	?	68·9	6·542

The above table shews that the conditions of the atmospheric column over Northern India, relatively to that over Ceylon, are alternately as those of the columns AC, BD, in the figure on page 168 to a column nearly mid-way between them ; and, as far as can be judged from the data given, these alternations are much more strongly marked in the Punjab than in Bengal. Over Ceylon, on the other hand, the change in the mean temperature and density of the column is very small; and, at one season of the year, the column is cooler and denser, at another warmer and rarer than that of Northern India.

83. Influence of temperature and humidity on atmospheric density.—We have seen, in §§ 5 and 8, that the density of air may be lowered without any reduction of its tension, either by raising its temperature or by the substitution of vapour for dry air. And it is a question of no small interest, in connection with the theory of the monsoons, in what measure these two causes respectively contribute to bring

about that annual variation in the density of the lower atmosphere, which is illustrated in the foregoing table. A column of air 7,000 feet high above sea-level, between Darjeeling and Goalpárá, which equilibriates 6·697 inches of mercury in January is equivalent to only 6·365 inches in July: hence its density is reduced in the proportion of those figures. A part of this reduction of density is, however, accounted for, by its reduced tension; since, at 7,000 feet, the superincumbent barometric pressure is 23·329 inches in January and only 23·220 inches in July. Were the composition and temperature of the atmosphere to remain unaltered, the barometric weight of the column, by this change of top-pressure, would be reduced from 6·697 to 6·665 inches. The remainder of the reduction is due to the increase of temperature, and the increased charge of vapour; mainly, indeed, to the former; for, assuming that the mean temperature of the column is accurately represented by the figures in the foregoing table, we have by Charles' law, (§§ 5, 7,)—

$$\frac{461{\cdot}2+6{\cdot}411}{461{\cdot}2+73{\cdot}81}\times 6{\cdot}665=6{\cdot}411$$

leaving only $6{\cdot}411-6{\cdot}365=0{\cdot}046$ inch, as the reduction in the barometric weight of the column, to be accounted for by the substitution of vapour for air. The final result is, then, as follows:—

		Inch.
Barometric weight of column 7,000 ft. high, in January	...	6·697
Reduction in July due to reduction of tension ...	...	0·032
„ „ increase of temperature ...	...	0·254
„ „ increased humidity[1] ...	...	0·046
Total reduction in July	...	0·332

84. Annual variation of pressure at hill stations.—The annual oscillation of pressure at the hill stations, in all parts of India, is different from that on the plains. With very few exceptions, the highest pressure occurs in December everywhere on the plains of India; that of January being nearly as high; and the lowest in June or July. But, on the hills, the pressure in December is almost universally below that of November; and the further fall in January and February becomes more and more decided as we ascend to greater heights. At Leh (11,500 feet above the sea) the pressure of February is the absolute minimum of the year. At stations of 6,000 ft. elevation and upwards, (frequently at lower altitudes,) the pressure rises again after February to a second maximum in March or April; but this maximum is, in all cases, subordinate

[1] In a paper on the 'Winds of Northern India,' in the 164th volume of the Phil. Trans., the value of this datum was computed independently from the psychrometic observations, and with practically the same result.

to that of November. Like the February minimum, it is most decided at Leh; where, (on the mean of two years,) there is a difference of ·134 between the mean pressure of February and that of April. The following table will illustrate these facts. It shews the annual variation of the mean monthly pressure, (not reduced to sea-level,) at Colombo, Nagpur, Calcutta, Goalpárá, and Roorkee, as representing the plains, and at Newera Eliya, Pachmarhi, Darjeeling, Simla and Leh, as instances of elevated stations, in different parts of India.

Months.	Plains.					Hills.				
	Colombo, 42 feet, 6 to 7 years.	Nagpur, 1,025 feet, 7 years.	Calcutta, 18 feet, 11 years.	Goalpárá, 386 feet, 7 years.	Roorkee, 886 feet, 9 years.	Newera Eliya, 6,150 feet, 5 to 6 years.	Pachmarhi, 3,504 feet, 2 years.	Darjeeling, 6,912 feet, 7 to 9 years.	Simla, 7,071 feet, 3 years.	Leh, 11,538 feet, 2 to 3 years.
January ...	29·862	28·941	30·011	29·614	29·118	24·080	26·517	23·383	23·225	19·598
February ...	·865	·901	29·948	·548	·053	·089	·527	·370	·193	·568
March ...	·853	·812	·856	·464	28·968	·097	·482	·365	·197	·606
April ...	·812	·712	·757	·387	·858	·077	·391	·364	·207	·702
May ...	·802	·629	·665	·304	·743	·067	·327	·336	·146	·674
June ...	·801	·538	·550	·212	·618	·046	·237	·274	·061	·631
July ...	·823	·542	·545	·196	·636	·043	·184	·270	·069	·609
August ...	·828	·609	·608	·257	·697	·045	·271	·311	·101	·627
September ...	·848	·651	·689	·341	·798	·059	·316	·369	·194	·686
October ..	·846	·801	·831	·451	·960	·059	·479	·428	·227	·715
November ...	·855	·949	·980	·596	29·106	·091	·556	·472	·293	·767
December ...	·868	·979	30·030	·635	·149	083	·579	·444	·254	·711

These facts indicate that, at levels of little more than one-third the average height of the Himálaya, the annual variation of pressure is so different in character from that of the plains, that it is impossible to consider that, at these heights, the alternations of the monsoons assimilate to those at lower levels. The chief feature of the difference consists in the barometric depression of the winter season, which is felt above elevations of 5,000 or 6,000 feet; and, in the north-western Himálaya, sets in in November, and attains its minimum in February. The reduced density of the summer atmosphere extends to, and influences the pressure to a much greater height than does the increased

density of the winter months; for, even at the greatest elevation for which we have as yet any registers, there is a fall of pressure from April to June and a rise to November. The meaning of the former fact is, that the high pressure of the atmosphere on the plains of India in December and January, is entirely due to the greater average density of the strata below 6,000 feet; while, above that altitude, the average density is even lower than in November. How is this latter fact to be explained? It has been remarked above, that the density of the atmosphere may be lowered either by an increase of its average temperature, [§ 5] or by the intermixture of a larger proportion of water vapour, which, for the same elastic tension, has a smaller density [§ 8]. But since, during the greater part of December, the sun is still retreating in southerly declination, and since, moreover, the great source of vapour lies to the south, in either case, the lower density of the higher atmosphere can be explained only on the supposition that a more copious upper current flows from that direction; and that such is the case, is confirmed by other phenomena, such as the direction of the winds on the Himálaya, the increased relative humidity and cloudiness of the skies in Upper India, and the occurrence of the cold weather rains, which will be noticed in a subsequent part of this treatise.

As far as the existing observations of wind direction and the movements of the clouds over the Himálaya afford any additional evidence, they support this view. In October and November, the winds and movements of the high clouds over the mountains appear to be chiefly from the north-west; and this is the case so long as the sky and mountain tops remain unclouded. But in December, or sometimes a little later, the hill stations become clouded, snow falls, and the current is then from the south-west or some other southerly quarter.

85. The anti-monsoon.—This current is the *anti-monsoon*, the upper return current, corresponding to the anti-trade, which, in Western Europe, prevails during the winter months, and while it raises the temperature and lowers the pressure in virtue of its diminished density, brings also the snow and rain, which then fall more copiously than at any other time of year. The anti-monsoon probably takes its rise in the belt which, in the winter months, intervenes between the south-west trade of the South Indian Ocean and the north-east monsoon of the Indian seas; but very little is known at present of the upper currents over India, and careful and prolonged observations on the drift of the higher clouds are much required to throw light on this subject.

The high pressure of December and January on the plains of India is explained, then, by the cooling and condensation of the lowest layer of this air current; but it is very probable that the winter anti-monsoon plays a more important part in the meteorology of Asia, than merely to supply the place of the air that flows from the Himálayan slopes and plains of India southward to equatorial regions. The Himálaya is, indeed, an impassable barrier to any interchange of air currents between India and Central Asia, in the lower half of the atmosphere; but not to that loftier stream, which, in the winter months, sweeps over the peaks of the snowy range, clothing them with the long feathery cloud banners, which may be seen streaming away to the north-east from such giants as Kinchinjunga and its attendant peaks. Observations are, indeed, as yet wanting for the lofty table-land which lies beyond in the path of the current; but it is hard to believe that, so deep and steady a flow of air serves no other purpose, than to feed the gentle outflow of the north-east monsoon of Southern Asia.

86. Vertical thickness of the monsoon currents.—The facts recounted in the foregoing paragraphs, point to the conclusion that the depth of the north-east monsoon in January and February, in the neighbourhood of the hills, is less than 7,000 feet; and, on the other hand, since the summer reduction of pressure is felt very decidedly at not less than 11,500 feet above the sea, it is probable that the monsoon of that season flows in a stream of much greater depth. A comparison of the pressures at Newera Eliya and Darjeeling will enable us to fix with some approximation the height of the neutral plane of pressure (represented by EF in the diagram, figure 9,) at the two seasons, between these two stations. It does not follow that it should hold the same relations to intermediate places; but it must be the limit of any current flowing uninterruptedly between the two places compared. If, for the sake of easy comparison, we substitute for the observed pressures, the computed pressures at the sea-level and at 7,000 feet (the differences of which are given in the table at page 170); and if we assume that, up to certain moderate heights in a vertical direction, the differences diminish in the same proportion as the total pressures, then the mean pressure in the neutral plane between Ceylon and Sikkim will be as shewn in the following table; omitting the months March, April and October, which may be regarded as months of transition. It will of course be understood that the figures represent only *an average*, and that the actual depth of the monsoon is probably subject to great variations, as also is the direction of the winds during its prevalence.

Computed mean elevation of pressure equilibrium between Ceylon and Sikkim.[1]

Season.	Month.	Computed mean pressure at 7000 feet.			Computed mean pressure at sea-level.			Neutral plane.	
		Ceylon.	Sikkim.	Difference, Sikkim and Ceylon.	Ceylon.	Lower Assam.	Difference, Assam and Ceylon.	Pressure, Ceylon and Assam.	Approximate Elevations in feet.
Winter monsoon.	November ...	23·360	23·420	+·060	29·898	30·002	+·104	14·44	19,500
	December ...	·351	·391	+·040	·911	·045	+·134	21·52	9,100
	January ...	·348	·329	−·019	·905	·026	+·121	24·20	5,900
	February ...	·358	·317	−·041	·908	29·955	+·047	26·41	3,500
Summer monsoon.	May ...	·340	·285	−·055	·845	·698	−·147	19·45	11,850
	June ...	·316	·223	−·093	·844	·604	−·240	19·17	12,200
	July ...	·312	·220	−·092	·866	·585	−·281	20·12	10,900
	August ...	·315	·261	−·054	·871	·647	−·224	21·23	9,500
	September ...	·329	·318	−·011	·891	·735	−·156	22·82	7.500

It is important to observe that the barometric differences between the pairs of stations compared in the table do not represent the whole average gradient of the monsoon. In the rains, the pressures over the plains south of the Himálaya, and more especially in the Punjab, are considerably lower than in the neighbourhood of the Sikkim Himálaya, allowing for the differences of elevation; and it is not only conceivable, but even highly probable, that the neutral plane between Ceylon and the seat of lowest pressure may be at a greater elevation than those shewn in the table.

In January and February the average height of the neutral plane, as shewn in the table, is below the level of Darjeeling; as might be anticipated from the prevalence of the anti-monsoon at that station, referred to in § 80. But the pressure in the Punjab and Central India, in these months, is higher than in the neighbourhood of the Sikkim Himálaya; and it is probable that the elevation of the neutral plane, as compared with Ceylon, is there greater. For the verification of these inferences,[1] we must await the collection of a sufficient series of trustworthy barometric observations at such stations as Chakráta, Murree, Mount Abu, Pachmarhi, and Wellington on the Nilgiris.[2]

[1] See note at the end of this Chapter.

[2] I might have discussed the data afforded by Simla and Roorkee, but on comparing the mean barometric values at the former station, given (from Colonel Boileau's observations) in the table on page 172, with those of Chakráta for last year, I find that the former are throughout so much lower, that I am doubtful whether they can be accepted in evidence on this point. Chakráta is so near Simla (50 miles off), and so nearly at the same elevation, that a much closer general correspondence might be expected. Even although the readings are somewhat too low, they may nevertheless be taken as showing the annual variation at the place; for which purpose they are given in the table above referred to.

87. Annual redistribution of pressure.—Alternately, at the opposite seasons of the year, the Punjab is the seat of the highest and lowest pressure at the ground surface, due allowance being made for altitude; and the facts, already recounted, shew that this oscillation mainly depends on its being alternately the seat of the lowest and the highest temperature. In other parts of India, the summer fall of pressure, in many cases, is less characteristically proportional to the winter excess, and there appears to be one tract, *viz.*, the South Mahratta Country and Mysore, in which the pressure is relatively high throughout the year. The accompanying figures, which are a reduction of the isobaric charts for India, in January and August 1875, fairly represent the average distribution of pressure in those months.

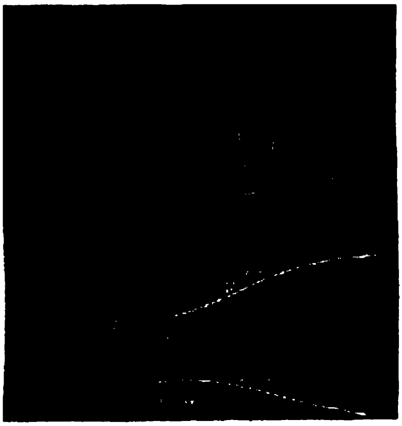


Fig. 10.—Isobaric chart of India in January 1875.

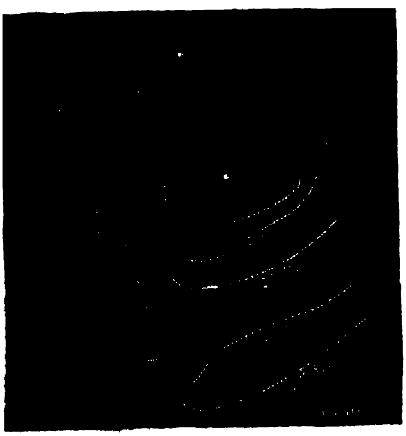


Fig. 11.—Isobaric chart of India in August 1875.

The tract of high pressure in the Central Provinces appears to be a recurrent feature of the winter season. It varies somewhat in position, but generally lies on an axis extending from the Punjab through the Central Provinces to Orissa. A high pressure also prevails in Upper Assam; while, in the Gangetic delta, and sometimes the lower part of the Gangetic valley, there is a tendency to a low pressure, more or less, all through this season. The lowest pressure is in the extreme south of the Bay of Bengal. In February and March the pressure falls about 0·2 or 0·3 over the land, but to a much less extent over the Bay of Bengal; and, in the latter month, it is, as a rule, higher over the middle of the Bay than either over India or the equatorial sea to the south. On the land, the pressure is lowest in the neighbourhood of Nágpur, and also in Chutia Nágpur or that direction; and a trough of low pressure extends up the Ganges valley, or somewhat to the south of it. But it remains a little higher in the region of the Nerbudda and Rájputána, and this local elevation of pressure lasts throughout the

hot weather, notwithstanding that it coincides in position with the seat of highest temperature (see figure 2 page 149).

During this season, the pressure continues to fall, and more rapidly in the Punjab than elsewhere; until, in June, there is a difference of about half a barometric inch between the south of the Bay of Bengal and the Punjab (after allowing for elevation). The relative distribution of pressure undergoes but little change during the rains, except that it rises gradually after June or July, and most so in the Punjab; until, about the end of September or the early part of October, a rapid rise in this region transforms it from the seat of the lowest to that of the highest pressure. This rise is general over Northern India, but the southern part of the Bay remains unaffected; and, in most years, the Bay becomes an area of low average pressure, completely circumscribed by slightly higher pressures. This is essentially the season of the cyclones of the Bay; and thus, the explanation of their frequency is, in part, to be found in the distribution of pressure, above described. The further rise in November and (on the plains) in December, restores the distribution characteristic of the winter monsoon.

88. Annual variation of the winds.—All persons who have resided much in India are aware that the distinctive names, *north-east* and *south-west*, originally given to the monsoons by sailors, are, in a great measure, misnomers in the interior of India. On the Gangetic plain, the so-called *north-east monsoon* blows from the north-west, and the *south-west monsoon* from the south-east or east; while, over the western part of the peninsula, the former is almost due east, the latter due west, or even from north of west. It would be a great convenience, in speaking of the meteorology of the land, were these terms altogether dropped, and the equally distinctive and less misleading terms "winter" and "summer" substituted for them. In the further description I shall use these terms in preference.

89. Winter monsoon.—In November and December, the months in which the winter winds are most steady in the Upper Provinces, they radiate out with a certain anti-cyclonic curvature from the region of high pressure in the Punjab; but their velocity is very low; and here, and, indeed, throughout the Upper Provinces, the air is very frequently calm. Down the Gangetic plain they are from north-west or west-north-west; but south of the Satpuras, the winds are easterly, and this is the prevailing direction throughout the peninsula. The tract of high pressure in the Central Provinces, before adverted to [Fig. 10] separates the westerly from the easterly currents; and here, and to the east of it, in Orissa and Bengal, the winds are chiefly north and north-east; while, in the upper half of

the Bay, either they have the same characteristic direction from the north-east, or else calms prevail.

The following table shews the mean movement of the winds, as registered at a few stations representing different parts of India, in the four months November to February :—

Mean daily movement of wind in miles, winter moonsoon.

Month.	Dera Ismail Khan, 4 years.	Lahore, 3 to 4 years.	Roorkee, 4 to 5 years.	Agra, 5 years.	Lucknow, 3 to 4 years.	Patna, 4 to 5 years.	Hazaribagh, 6 to 7 years.	Berhampore, 4 to 6 years.	Goalpara, 6 to 7 years.	Dacca, 7 years.	Chittagong, 6 to 7 years.	Calcutta, 6 to 8 years.
November ...	18	56	27	52	25	50	84	30	95	41	91	85
December ...	19	60	30	57	29	50	91	27	83	46	107	91
January ...	51	67	54	83	61	63	103	37	84	51	119	98
February ...	59	89	69	92	73	85	134	47	107	65	131	98

Months.	Saugor Island, 4 to 6 years.	Cuttack, 4 to 5 years.	Raipur, 4 to 6 years.	Nágpur, 5 to 7 years.	Seoni, 6 years.	Jubbulpore, 6 to 7 years.	Hoshangabad, 5 to 6 years.	Chanda, 5 to 6 years.	Bombay, 6 years.	Madras, 5 years.	Akyab, 3 to 4 years.	Port Blair, years.
November ...	112	37	44	65	64	50	46	35	237	208	50	190
December ...	130	32	41	56	69	53	59	32	234	228	57	127
January ...	134	45	60	65	65	65	59	43	244	172	67	159
February ...	191	57	71	90	64	70	61	55	257	172	80	111

It will be noticed that, in a majority of cases, more especially in Upper India, there is a considerable increase in the movement of the air in January; and yet the registers of wind direction shew that, both in this and the following month, the winds are far less steady than in November and December. The fact appears to be that, in the last two months of the year, the winds are a steady outflow of cooled air, true convection currents; but that in January and February, with the rising temperature, this is no longer the case. The general southerly set of the surface currents ceases, and merely local variations in the thermal behaviour of the surface become of preponderant importance. At the some time, in the south of the Bay, the north-east monsoon blows with more steadiness than either in November or December.

90. The summer monsoon.—The north-east monsoon is followed by an interval of three or four months, in which the prevalent winds of Northern and Central India are from the west and north-west. These

are land winds, characteristic of the dry hot season, and have no relation to the monsoons; and I reserve their further discussion for the present. During their prevalence in the interior, the sea winds, which, at first, are diurnal winds and restricted to the neighbourhood of the coast, become more and more persistent and penetrate further and further inland; more especially in the lower part of the Gangetic valley, and along the face of the mountain belt, where they blow from east and south-east; and, finally, a more copious rush of saturated air, from the far south, invades the greater part of India and ushers in the rains: such, at least, is the course of the changes in Bengal and the Upper Provinces. On the west coast and in Central India, the setting in of the rains is a more striking phenomenon, though the change of wind direction is but small; it consists in the rapid substitution of a saturated west or west-south-west wind for an exceedingly dry north-west wind; which change is accompanied by a considerable fall of pressure as well as of temperature. On the Madras coast, again, the changes are somewhat different. Here, during the spring months, the land and sea winds blow alternately with much regularity near the coast; and on the high Mysore plateau, hot diurnal land winds prevail from the east. But, on the setting in of the summer monsoon, these give way to westerly winds, all across the peninsula; while, on the Coromandel coast, the prevailing direction is south-west. These are the long shore winds.

The summer monsoon has a greater average velocity than that of the opposite season, as well as greater depth and volume, but a lower velocity than the winds of the hot season. Throughout the greater part of the peninsula and in the Central Provinces,—indeed, wherever the winds come from the western coast, and preserve their westerly direction,—the velocity is higher than in the northern provinces, where they come from the Bay of Bengal and in an easterly direction. This is shewn in the following table :—

Mean daily movement of wind in miles, summer monsoon.

Months.	Dera Ismail Khan.	Lahore.	Roorkee.	Agra.	Lucknow.	Patna.	Hazaribagh.	Berhampore.	Goalpara.	Dacca.	Chittagong.	Calcutta.
June ...	67	111	104	129	109	110	210	145	129	197	185	192
July ...	63	109	78	117	108	93	188	122	97	192	182	157
August ...	53	99	65	117	57	94	162	101	102	150	155	129
September	44	76	54	106	64	94	153	89	102	118	119	124

Months.	Saugor Island.	Cuttack.	Raipur.	Nágpur.	Seoni.	Jubbulpore.	Hoshangabad.	Chanda.	Bombay.	Madras.	Akyab.	Port Blair.
June ..	320	113	154	161	135	149	86	118	433	269	91	279
July ...	292	89	165	171	127	135	73	122	482	260	82	296
August ...	247	69	129	132	100	123	69	92	412	217	70	256
September	222	61	119	110	82	91	52	70	289	198	65	251

Of the two branches of the monsoon, that which comes from the Arabian Sea blows right across the peninsula. Even in Orissa, the greater part of the rain is brought from that direction. It holds possession, on an average, of the plateaux on both sides of the Sátpúras, and extends almost to the confines of the Gangetic plain. Even at Jhansi, westerly winds are more frequent than east winds in the summer monsoon. It blows from the south-west across the western part of the Malwa plateau, along the Aravalli range, and over the Thur desert beyond; but in this latter tract and Sind, west winds are on the whole quite as prevalent. The branch of the monsoon which comes from the Bay of Bengal, prevails in Burma and Arakan, in Eastern Bengal and Assam, the Gangetic delta and the Gangetic plain; but in the last area not exclusively; for much of the rain of this season, and indeed some of the heaviest falls, come with a south-west wind. In the upper Gangetic valley and the Punjab, the two currents seem to coalesce; and around the plain of the five rivers, the tendency of the winds is distinctly cyclonic.

It must not, however, be supposed that each branch of the monsoon blows steadily over a certain more or less defined tract—at least in the upper half of India. On the contrary, the whole of this region is more or less debatable ground; and it would appear that, during the monsoon rains, it is constantly traversed by what we may term *land cyclones*, of low intensity, which seem to be formed in the belt of low pressure which lies on an average to the south of the Ganges, and to traverse the country for a greater or less distance, lasting several days, and moving on a general track towards the west or north-west: such at least was the case during 1875, the only year that has as yet yielded sufficient materials for investigating this subject. These cyclones are accompanied by heavy rain, and in the neighbourhood of the vortex the velocity of the wind is considerably above the average; but, even here, it does not appear as a rule to exceed 20 miles an hour, and is generally lower.

91. The monsoons on the Bay of Bengal.—The manner in which the monsoons set in over the Bay of Bengal has been correctly described by Maury,[1] exception being taken to some expressions which may be understood to imply that currents drawn from different quarters towards the same spot, are impelled by some other force than mere differences of local pressure. North-east winds are felt in the north-west corner of the Bay as early as October, a month in which the mean pressure over the Bay is lower than on the surrounding land (except, perhaps, the Carnatic), and lower also than in the neighbourhood of the equator. Hence, the general tendency of the winds is to circulate cyclonically around the Bay; and the north-east winds, which, at False Point, amount to about 28 per cent. of the observations, are only the local direction of the circulation. Between the equator and 5° north latitude,—that is, to the south and south-east of Ceylon,—the direction is almost exclusively westerly, varying between north-west and south-west; and, over the Bay itself, the winds are light and variable, calms alternating with storms. As the pressure continues to rise in Bengal, northerly winds advance further down the Bay; but they are, in general, light; and the north-east monsoon never has the violent stormy character that distinguishes it in the China seas. Northerly winds do not predominate down to the equator till the latter part of December or the beginning of January. Later on in this month, on the coasts of Bengal, the steady northerly wind is coming to an end, and sea winds begin to alternate with it in the afternoon. Little by little, these winds are drawn from a greater distance at sea; and, more especially in the north-east corner of the Bay, these south-west winds blow with great force in the month of March, sometimes rising to a gale. In this month the relations of pressure over the Bay are precisely the reverse of those of October. It is the seat of the highest pressure; and the tendency of the winds is, on the whole, anti-cyclonic. At Port Blair, 59 per cent. of the winds are from north-east; while at False Point, 50 per cent are south-west, and at Akyab 56 per cent. from west, north-west, or north. In April and May, the general fall of pressure over the land extends further and further to sea; and south-westerly winds become more and more prevalent. In May and June they predominate to the extent of 64 and 78 per cent. down to 5° north latitude, and 49 and 59 per cent. respectively down to the equator. The relative prevalence of the winds in the Bay and down to the equator is admirably shown in the following table, which is extracted from that given by the late Lieutenant Cornelissen in his valuable work "Route voor stoomschepen van Aden, &c." The first table gives the winds between east longitude 80° and 90°, on the western

[1] Phys. Geog. of the Sea, 12th edition, page 368.

half of the Bay; the second those between 99° and 100° or in the eastern half, in successive strips of 5° latitude, down to the equator.

Winds between 80° *and* 90° *east longitude.*

Latitude.	Winds.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.
15° to 20°	North to east ...	63	43	28	6	5	2	1	3	7	37	74	68
	East to south ...	9	11	19	18	20	9	5	10	16	20	6	1
	South to west ...	10	27	33	66	68	88	84	75	58	22	8	8
	West to north ...	14	15	16	7	6	4	10	11	17	16	10	22
	Calms ...	4	4	9	3	1	2	...	1	2	5	2	1
10° to 15°	North to east ...	79	67	50	17	7	1	...	1	4	26	52	72
	East to south ...	11	18	22	35	20	8	5	11	9	25	23	16
	South to west ...	3	7	10	31	59	80	85	64	73	29	8	4
	West to north ...	5	6	10	9	9	7	6	23	13	12	16	6
	Calms ...	2	2	8	8	5	4	4	1	1	8	1	2
5° to 10°	North to east ...	72	76	58	25	4	1	1	1	1	16	81	47
	East to south ...	12	11	19	29	14	7	4	13	3	15	20	20
	South to west ...	7	5	7	31	64	78	76	74	81	49	22	10
	West to north ...	7	6	12	11	16	11	18	11	14	18	21	20
	Calms ...	2	2	4	4	2	3	1	1	1	2	6	3
0° to 5°	North to east ...	54	53	40	16	3	...	...	...	4	8	16	46
	East to south ...	12	14	17	21	16	25	16	19	17	8	10	8
	South to west ...	11	7	10	33	49	59	65	56	58	48	35	26
	West to north ...	21	22	23	24	25	15	17	22	20	35	35	19
	Calms ...	2	4	10	6	7	1	2	3	1	1	4	1

Winds between 90° *and* 100° *east longitude.*

Latitude.	Winds.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.
15° to 20°	North to east ...	55	42	12	5	1	...	...	2	13	37	66	69
	East to south ...	3	4	7	7	10	12	2	1	8	18	15	2
	South to west ...	8	12	14	44	65	80	91	90	61	12	4	4
	West to north ...	29	36	60	33	17	5	6	6	13	28	14	24
	Calms ...	5	6	7	11	7	3	1	1	5	5	1	1
10° to 15°	North to east ...	78	53	42	29	7	...	2	...	...	22	53	83
	East to south ...	6	3	8	13	6	9	5	6	4	20	18	8
	South to west ...	...	4	8	24	63	82	87	79	77	25	10	1
	West to north ...	12	36	33	27	16	8	5	14	15	27	17	7
	Calms ...	4	4	9	7	8	1	1	1	4	6	2	1
5° to 10°	North to east ...	66	65	64	24	4	1	5	6	2	21	48	72
	East to south ...	12	8	11	22	12	17	18	14	11	16	22	12
	South to west ...	4	3	7	22	67	71	68	63	56	33	9	2
	West to north ...	15	20	12	24	11	10	8	11	27	26	16	13
	Calms ...	3	4	6	8	6	1	1	6	4	4	5	1
0° to 5°	North to east ...	34	28	27	11	5	4	8	5	3	11	15	22
	East to south ...	11	9	18	16	18	23	18	14	16	21	15	13
	South to west ...	17	19	17	42	51	58	46	54	62	29	27	16
	West to north ...	31	31	28	23	20	10	20	16	13	31	38	36
	Calms ...	7	13	15	8	6	5	8	11	6	8	5	13

92. The monsoons on the Arabian Sea.—Since the atmospheric pressure over the peninsula is lower than on the seas around in the summer months and higher in the winter months, the direction of both monsoons in the neighbourhood of the west coast is modified by the tendency of the winds to become cyclonic in the former season and anti-cyclonic in the latter. The summer monsoon, then, instead of blowing from south-west, or even south-south-west, as on the coast of Arakan, is, on an average, west and west-north-west; and frequently from north-west, on the west coast of the peninsula. It is somewhat more southerly in the neighbourhood of Bombay than on the coast of Malabar; and, out at sea, to the west of the Laccadives, its direction varies between west and south-west. On the Arabian coast it is south-west. The winter monsoon is very light down the Malabar coast, from the north-west or north, becoming north-east or north-north-east out in the open sea.

During the height of the south-west monsoon, there is a tract lying between the equator and 9° north latitude, and extending nearly from Ceylon to Socotra, in which the winds are light and the sea smooth. This is known to navigators as "the soft place in the monsoon," and is taken advantage of, more especially by steamers, proceeding westward towards the entrance of the Red Sea. To the north of this, the monsoon blows in the direction above described with great force. It is not yet known what is the physical explanation of this phenomenon, and we must await the light that will undoubtedly be thrown upon it by the discussion of the official logs collected by the London Meteorological Office, and which are now in course of preparation.

93. The land winds of the interior.—In the spring months, when the temperature of the land, more especially of Rájpútána and Central India, is considerably higher than that of the seas around the peninsula, the pressure of this hottest and driest tract is nevertheless higher than that of the cooler maritime belt and the neighbouring seas; and dry winds, which, in Northern India, are steadily from the west or north-west, blow with considerable force from this region towards Bengal and the Central Provinces south of the Satpuras; thus forming an exception to the law of winds in general, which is, that they are produced by convection, and that the seat of highest temperature is also that of lowest pressure and of ascending currents. Such are the well-known hot winds of April and May. They are characteristically winds of the day-time. They spring up about 9 or 10 in the morning and blow with considerable force till 4 or 5 in the evening, frequently indeed later, and occasionally far into the night. But, as a rule, the nights

are comparatively cool and calm, and there is, at most, a gentle westerly zephyr, though upper currents may sometimes still be observed to set from the same direction. After March, and, indeed, during that month, the land winds are rarely felt down to the coast line; and in Lower Bengal, for some distance from the coast inland, the sea breeze prevails; sometimes blowing night and day. The hot land winds are doubtless of similar origin to those of South Australia, and of dry desert tracts in other parts of the world; but hitherto, with the exception of Mr. Laughton, they have met with little attention at the hands of meteorological writers. For the views of that writer, readers may refer to his work on "Physical Geography in relation to the prevailing winds and currents,"[1] and also to his paper in the Philosophical Magazine, referred to below. How far I agree with, and differ from, those views, will be apparent from the subsequent discussion. In the explanation of land and sea breezes given at the beginning of this chapter, we saw that one effect of the diurnal heating of the land and sea surface is to expand the lower strata of the atmosphere unequally, and to disturb the isobaric planes in such a manner as to produce a current blowing from the land to the sea at a certain height in the atmosphere; and, as a subsequent effect, a current setting in from the sea towards the land in the lower strata. The existence of both of these currents may be verified by observation, that of the higher current being rendered apparent by the motion of the loftier clouds, and, not infrequently, even by the summits of the cumulus, being drifted in a seaward direction. The sea breeze penetrates gradually inland as the day advances; but, beyond 20 or 30 miles, it is no longer felt as a distinct daily wind from the sea, although its influence may still be perceptible in the anemographic record. This is the case, for instance, at Calcutta, where, during the hot dry months, the wind has a decided tendency to back from south-west to south late in the afternoon; and to blow from that quarter, for some hours, with gradually diminishing strength. But during the hottest hours of the day, and especially on dry hot days, the wind is from the west; and the further we advance towards the interior, the more prevalent is this westerly wind.

I have already mentioned that, when it is felt as a hot wind, the land wind sets in about 9 or 10 in the morning,—that is to say, about or shortly after the hour of maximum diurnal pressure (§94); and, as a general rule, begins to decline between 4 or 5 in the afternoon, or about the time of minimum diurnal pressure; thus indicating that, to some extent, it is related to the diurnal oscillation of pressure: and we find,

[1] Phil. Mag. 1871, 4th Ser., Vol. XLI, p. 325.

on closer examination, that this relation is confirmed by the almost exact coincidence of the anemographic and barometric records.[1] Any satisfactory theory of the latter phenomenon will probably, therefore, throw some light on the causes of the former; and I shall defer, for the present, the further discussion of the land winds, and proceed to describe the diurnal oscillation of pressure, which is nowhere exhibited with more intensity and with more marked phases of variation than in India.

94. Diurnal oscillation of pressure (barometric tides).—It needs but to observe the rise and fall of the barometer for a day or two in almost any part of India, to learn the fundamental fact, that the atmospheric pressure undergoes daily a double oscillation; which is so regular in its occurrence that, except during the passage of a cyclone, it is very rarely indeed masked by the irregular or non-periodic variations. As we recede from the tropics towards the poles, the magnitude of this regular oscillation diminishes, while those variations of pressure which accompany changes of weather become more marked and of greater amplitude; so that, in European latitudes, the diurnal oscillation is quite a subordinate phenomenon, and indeed only to be detected by a close study of the barometric registers. The general character of the oscillation, as exhibited on the plains of India, is as follows: From between 3 and 4 in the morning, the pressure begins to rise, slowly at first, afterwards more rapidly; and it attains its maximum generally between 9 and 10 A.M., the exact hour varying at different seasons of the year. It then falls with great rapidity during 6 or 7 hours, and attains the lowest pressure of the 24 hours about 4 or 5 P.M.; the total fall in this interval being, on an average, rather more than 0·1 inch. Again, the pressure rises till about 10 at night, but this second maximum is somewhat less than in the morning. Finally, it falls again, but less rapidly than in the afternoon, and reaches a minimum between 3 and 4 A.M. Figure 15, page 167, part I, represents a plotted curve of the oscillation as observed at Jubbulpore, and figure 1, plate I, the mean curve in the month of April, at Calcutta, after the elimination of all non-periodic and irregular variations.

95. Variations of the diurnal oscillation.—The character of the oscillation, as observed on the plains of India, varies with the season of the year. The longer the day and the drier the atmosphere, the earlier is the forenoon maximum and the later the afternoon minimum, the greater the amplitude of the afternoon fall, and the greater also the inequality of the day and night oscillations. In the rains, although

[1] Winds of Calcutta. Indian Met. Mem., vol. i., p. 12.

the days may be as long as in the hot weather, or even longer, the morning maximum falls later, and the afternoon minimum earlier; the amplitude is reduced to its annual minimum, and the day and night oscillations are less unequal. Such appears also to be the character of the oscillation in mid-ocean.

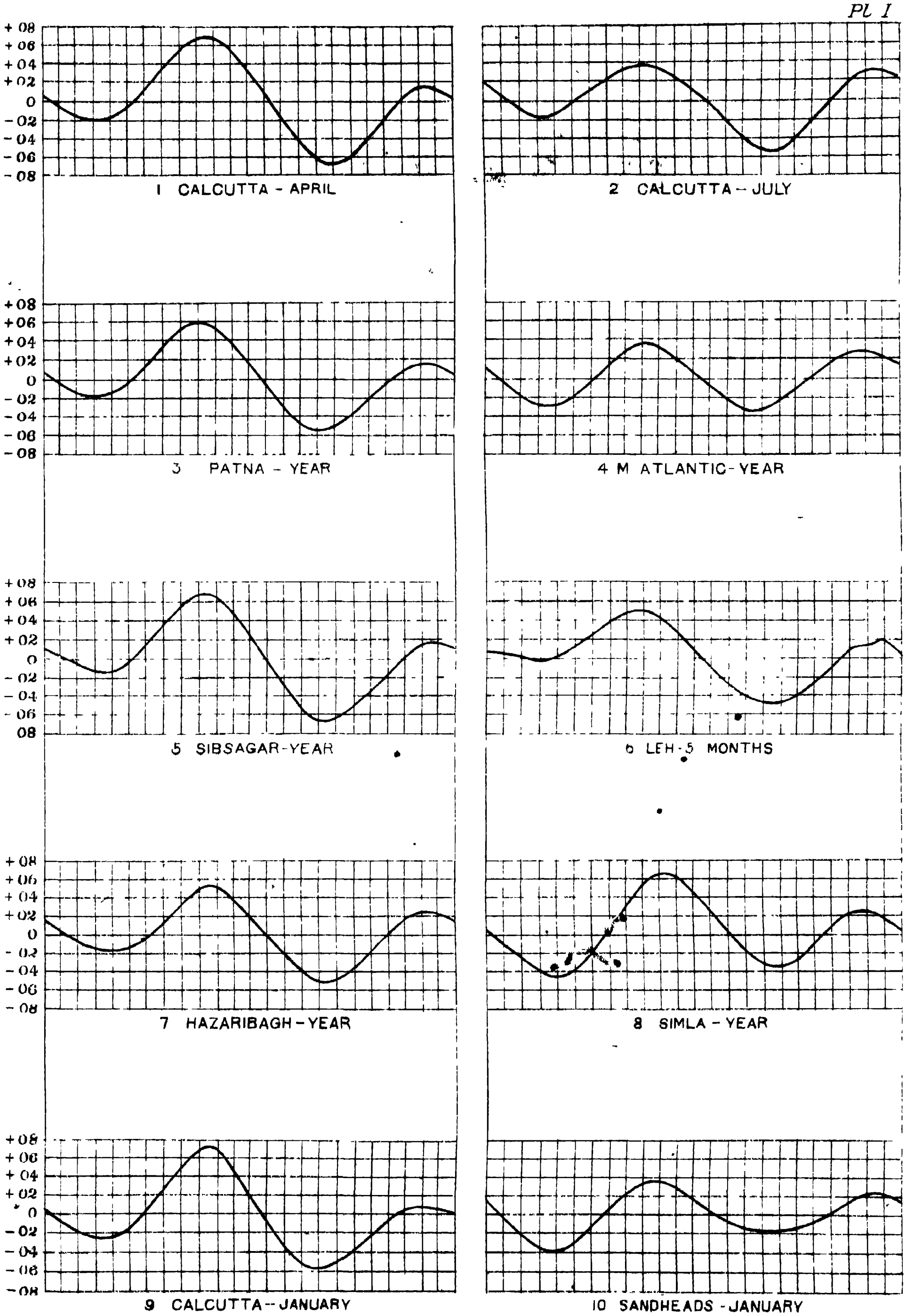
The amplitude of the afternoon fall appears to be greatest in certain valleys between mountains; as in Assam, where the climate is characteristically damp, and also at Ladák in the Upper Indus valley, where the climate is characteristically dry.

On low plateaux, such as that of Házáribágh, the character of the oscillation is similar to that on the lower plains, the amplitude being, however, less; but on mountain peaks and ridges, as at Simla, Darjeeling, &c., the early morning minimum is the absolute minimum of the day; and the amplitude of the forenoon rise of pressure is comparable with the afternoon fall on the plains, while the latter is of subordinate importance on the mountains. Very similar to this mountain curve, in respect of the relations of the two minima, is that of the sea, within a hundred miles or so of the land. Mr. Buchan pointed out the remarkable reduction which the afternoon fall seemed to undergo in the neighbourhood of coasts; but he was probably not aware of the relatively greater amplitude of the forenoon rise of pressure. It appears from such registers of marine observations as we possess, that the whole variation is less intense at sea than on land, and this to an extent which can hardly be accounted for by the greater friction of the mercury in the narrow tubes of marine barometers.

These several forms of the diurnal curve are illustrated in the accompanying plate. Figures 1 and 2 represent the oscillations at Calcutta in April and July; figures 3 and 4, the mean annual curves of Patna and the mid-Atlantic; figures 5 and 6, the mean annual curve of Sibsagor in Assam, and that of Leh for the 5 months August to December; figure 7, the mean annual curve of Házáribágh, which may be compared in point of amplitude with that of Patna; figure 8, the mean annual curve at Simla; and figures 9 and 10, that of January at sea about 100 miles from the coast of the Sunderbuns, and that of Calcutta in the same month, for comparison therewith.

96. Theory of the barometric tides.—We must dismiss from our minds any suspicion that may be suggested by the name, that the barometric tides have a common origin with those of the ocean; to which they have no other resemblance, than that of being a diurnal double oscillation. Doubtless, true gravitation tides are produced in the atmosphere

Pl. I



CURVES OF DIURNAL BAROMETRIC VARIATIONS.

(S. Sedgfield Lith. Calcutta)

by the attraction of the sun and moon; and indeed, observations conducted with proper precautions, have proved their existence. But the so-called tides of which we are now speaking are independent of the position of the moon, which is the more important body in the generation of true gravitation tides; and the fact above mentioned, that the epochs of maximum and minimum vary with the length of the day, indicate that the solar radiation, and not simply the attraction of the sun, is an important part of their cause.

Any satisfactory theory of the tides must account for the very marked variations noticed in the preceding paragraph, and illustrated on the plate; and must also distinguish between those oscillations of pressure which constitute the primary phenomenon, and such as are secondary and due to the transfer of masses of air between places where these primary oscillations are of unequal magnitude. All theories that have sought to account for these tides on the supposition that they are entirely produced by variations in the superincumbent mass, that they are changes in the static pressure of the atmosphere, have failed to account for the phenomenon; not only because the known forces in action are inadequate to produce the required transfer of air in the time allotted, but also because, in other respects, observation fails to confirm the requirements of these theories.

The expansion of the atmosphere by heating (and evaporation) in the morning sun, and the contraction and descent of the cooling mass in the evening and night, have been adduced as the probable cause of the double oscillation, independently, by Espy, Davies and Kreil. Their views have not met hitherto with general acceptance; and indeed, until it shall have been shewn by mathematical reasoning that the variations of pressure induced by these actions are not only real, but also *sufficient* to explain the observed phenomenon, we shall not be justified in adopting them, otherwise than as tentative explanations, for the purpose of guiding further inquiry. Lamont has computed the reactionary effect of an expanding atmosphere on the barometer; and finds that, unless some resistance be assumed, the effect is inappreciable; and resistance, according to his assumption, would produce a single oscillation of pressure only. But there is one important consideration which he, in common, I believe, with all previous investigators, has overlooked; and which seems to promise a more satisfactory solution, although at the present time it can only be considered as tentative. This is the retardation which the communication of pressure must undergo in the higher and colder strata of the external atmosphere. When the lower strata are heated or charged with

vapour, their pressure is increased according to the laws already explained. This effect is immediately followed by expansion; but the superincumbent strata are not lifted like a solid incompressible sheet. The excess of pressure is imparted successively from particle to particle; and with a velocity which cannot be greater than the rate at which a sound wave travels, and is probably considerably less. Now, the rate at which sound travels varies as the square root of the absolute temperature; being 1,090 feet per second, at the temperature of the freezing point. If, then, for the sake of clear exposition, we make the extreme assumption, that the outermost stratum of the atmosphere is absolutely cold; and if, further, the law of transmission of pressure holds good to this extreme limit of temperature, the result will be that an increase of pressure in any part of a vertical column of the atmosphere will eventually be distributed throughout the column; but with decreasing rapidity, especially towards the exterior; and the pressure, thus distributed, will not expand the atmosphere as a whole, for the external layer will remain unmoved, acting like a solid resistance. The height of the atmosphere will remain constant, but an increase of pressure will be transmitted daily from the lower and more heated strata, tending to such a distribution, that the pressure of every stratum shall be increased in the same ratio to its original pressure. Until such distribution shall have been accomplished, the pressure of the lower strata will be proportionally excessive; and the more so, the more rapidly it is increasing under an increasiug temperature or an increasing accession of vapour; and the slower the conduction. By the lower strata, I here mean not only those at and near the sea-level, but also those that extend up to a height of several thousand feet, in contrast with the lofty and attenuated strata, the temperature of which must be far below freezing, and in which the great retardation takes place.

It is not, however, necessary that we should assume the exterior of the atmosphere to be devoid of heat and perfectly rigid; all that is required is such a retardation in the transmission of pressure, that the accumulated excess of pressure at the sea-level should be about equal to that produced by half or three quarters of an hour's heating. Whether the probable conditions are such as will admit of this, is a question on which we are hardly in a position to pronounce at present; but the hypothesis is free from the objections that have been justly urged against those previously put forward, and is less vague and shadowy than the magnetic or electrical solar influence to which some physicists have appealed, apparently in despair of any satisfactory explanation based on thermal phenomena.

On the above hypothesis, the pressure at the ground surface would rise until a little after the most rapid rise of temperature, which precisely accords with observation. When the loss of pressure, by conduction, is exactly equal to the increase due to rising temperature, this would be the instant of maximum pressure; and the instant of minimum pressure would fall somewhat later than the maximum temperature, *viz.*, when the increased pressure due to the diurnal heating shall have reached its ultimate distribution, and in part, possibly, be spent in elevating the outermost strata of the atmosphere. The night maximum would then be produced very much as suggested by Kreil, *viz.*, by the dynamic pressure of the cooling atmosphere, sinking under the influence of gravity, and compressing the lower strata by the inertia of its descent; and the pressure would reach its maximum some time after the most rapid cooling; which also accords with observation. The morning minimum would occur when the movement ceases and the atmosphere is exercising a static pressure only. But the rise between 3 or 4 A.M. and sunrise is more difficult to account for, and I cannot say that any explanation that has yet been put forward seems to me to deal satisfactorily with this part of the phenomenon.

97. Causes of variation.—So far as the above explanation goes, it is of universal application; two oscillations would result; and the only variation which might be expected would be—1st, those differences in the magnitude of the oscillations which depend on latitude and the more or less direct action of the sun; and, 2nd, those which depend on whether the solar heat is used up chiefly in heating the air, or is absorbed as latent heat in evaporating cloud or the oceanic waters. This last variation might be anticipated from the considerations advanced in §22, 29; and the investigations of Kreil and Lamont shew that such is the case. They find that the mean amplitude of the double oscillation is less on cloudy than on clear days; and it has been observed above that it is greatly less over the sea than over the land. But over and above these differences, movements of the air are produced between neighbouring places where there is an inequality in these primary effects; and thus the phenomenon becomes complicated by changes of static pressure, which go far to explain the inequalities illustrated on plate I. That such movements take place is a matter, not of inference, but observation. Kreil demonstrated it in 1861 in the case of the wind registers of Prag, and more recently Mr. F. Chambers in the case of Bombay and some European stations, and the author in that of Calcutta.

The most important of these movements are, a daily transfer of air from the plains to the mountains, *viz.*, the mountain winds described in

§ 79; and that from the land to the sea, which is the immediate antecedent of the daily sea breeze, described in § 78. The first of these explains the peculiarity of the Simla oscillations; in which the afternoon fall of pressure is so much reduced by the access of air, that it is not so low as the morning minimum; (when the excess of air has been retransferred to the plains). And it is to be observed that this inequality is greatest in the driest months and least in the rains; just as the opposite inequality (the greater depth of the afternoon minimum) is on the plains. The second explains the remarkable difference of the tide at Calcutta and over the head of the Bay, which is of precisely the same kind as that between the mountains and plains. But, in this case, the inequality of the primary (double) oscillation being greater than in the case of the mountains, the transfer of air is also greater. The annexed woodcut, figure 12, gives the curves; figures 9 and 10, plate I, plotted on the same line of mean pressure in order to render more evident the oscillation of pressure between land and sea, which is otherwise expressed by the diurnal land and sea breezes. The figures shew in a very striking manner how, *cæteris paribus*, the pressure preponderates over the land (Calcutta) up to 1 P.M., after which it preponderates over the sea (between north latitude 20° and the Sand Heads) up to 1 A.M. The dotted curve represents the oscillation at Calcutta, the entire curve that at the Sand Heads. It appears probable that all the observed variations in the barometric tides may be explained by one or the other of the above considerations. Thus the exaggerated afternoon fall of pressure at places in deep valleys between mountains, (such as Sibsagor and Leh, figures 5 and 6, plate I,) is explained by the more copious diurnal transfer of air to the mountains on both sides, and the position of Házáribágh on the highest point of plateau, renders it to some small extent subject to the same influences as mountain stations.

Fig. 12.—Diurnal barometric curves at Calcutta and the Sand Heads.

98. Explanation of the land winds of the interior.—We are now in a position to understand the physical connection of the winds with the diurnal oscillation of pressure, which was suggested by their coincidence in point of time in § 93. In the first place, they blow from a region of higher towards one of lower mean pressure; and this difference doubtless depends partly on a persistent difference in the superincumbent mass, the static pressure, of the atmosphere; which, if unin-

terfered with, must tend to produce a steady but gentle wind. But the diurnal action of the sun renders this intermittent. The land wind is accelerated by the exaltation of the elastic tension of the lower atmosphere in the day-time, and blows outwards towards the sea, and also, especially at some elevation, towards all neighbouring mountains and highlands. In certain cases, again,—for instance, within one or two hundred miles of the sea,—it blows towards the same goal as the sea wind; and, rising with the latter in a convection current, pursues its course towards the sea above the level of the latter; and it is probable, as, indeed, was long since suggested by Kreil, that even minor variations in the thermal character of the land surface, such as broad rivers, &c., play a part in determining its prevalence. In the night, the tendency of the wind is in the opposite direction, and the result is either a simple lull of the lower atmosphere, while, possibly, an inflow of upper currents is active, or equilibrium is restored by the valley winds from mountains, a general convective descent of cooler air; or an actual light easterly wind, such as is frequently felt in the plains in the early morning hours, as a precursor of the rains.

99. High pressure of Rajputana.—The relatively high pressure of this tract in April and May, when it is also the seat of the highest temperature, has already been referred to as affording a striking exception to the general law, that regions of high temperature are also those where the density of the atmosphere is low and the pressure, therefore, also low. The explanation appears to lie in the fact, that the high temperature is restricted to that stratum of the atmosphere that rests on the ground surface; and that, owing to the dryness of the atmosphere, the vertical decrement of temperature is comparatively rapid; so that, at a moderate height, the temperature may be lower than over the region of the lower pressure in the Punjab, and the mean density of the atmosphere higher. For the verification of this view, we must await the information which will shortly be available in the registers of the observatory lately established on Mount Abu. Meanwhile it is to be remarked that all over Central India, the setting in of the rains is accompanied by a sudden and considerable fall of pressure, and also of surface temperature; the former amounting to nearly 0·1 inch on the average of the months, the latter to 14° or 15.° Having regard to the relations of temperature and pressure as elicited in § 83, the conclusion seems irresistible, that this fall of pressure must be owing to a rise of the mean temperature of the superincumbent atmosphere; despite the great cooling of the lowest stratum which rests on the earth's surface.

100. Irregular variations of pressure.—The irregular or non-periodic variations of pressure in India, as in most tropical countries, are in general so small, both absolutely, and also relatively to the periodical oscillations already described, that persons, whose experience of the barometer as a weather glass has been gained in England or other extra-tropical countries, are apt to conclude that its indications are altogether fallacious in India. This, however, is far from being the case. Although small, rarely exceeding 0·2 or 0·3 in the course of a month, (after deducting the diurnal oscillation,) they have an important meaning, and only require to be carefully interpreted and considered in their geographical relations—that is to say, as affecting different parts of the country in different degrees—to afford very important information relative to the weather changes in progress. So much may be stated with confidence; but the study of weather changes in India, except in connection with the cyclones of the Bay of Bengal, is at present almost a virgin field. It is only quite recently that it has been possible to obtain information of the daily changes from any wider area than a single Indian province; and, as yet, we are hardly in a position to draw any extensive general conclusions from the limited amount of data at our command. In some cases, indeed, it is certain that oscillations of pressure indicate the passage of cyclonic vortices, accompanied by the precipitation of rain over large tracts of country; but from the investigations of Mr. Broun lately published,[1] others would seem to be of such widely extended incidence, being felt simultaneously over a large area of both hemispheres, that at present we are quite incapable of assigning to them any probable physical explanation.

That irregular oscillations of pressure are not in all cases due to changes of static pressure,—that is, to changes in the mass of the superincumbent atmosphere,—is, I think, beyond question. Some of them occur so suddenly, and accompanied by such movements of the atmosphere, that it is difficult to account for them otherwise than by ascribing them to a dynamic cause. Of these, some very remarkable instances have lately been described by Mr. J. Elliott, and I cannot think it likely that the very common phenomenon of which the above are only extreme cases, *viz.*, the sudden rise of the barometer on the approach of a north-wester or other squall, is due to a descent of air either beyond the borders of the storm cloud, or beneath it. These are, however, at present, speculations to which no great weight can be attached. And this class of phenomenon, like that to which attention has been directed by

[1] Proc. Roy. Soc., vol. XXV, pages 24—39.

Mr. Broun, must be included, for the present, in the somewhat extensive list of unsolved problems, which Meteorology presents to her votaries.

101. Protracted irregularities of pressure.—We have seen, in § 87, that, year after year, each season is characterised by a certain scheme of pressure distribution, which determines the course of the winds at that season. But the distribution is not *exactly* the same in successive years, even when the temporary variations are in a great measure eliminated, by taking the mean pressures of a month (for instance) as the data for comparison. Nor, indeed, is it to be expected that it should be so. On the contrary, it is found that the relative pressures over certain tracts shew, sometimes a greater, sometimes a smaller, difference, and that these variations are sometimes protracted through many months. Thus, during the year 1868, the north-west corner of the Bay of Bengal and a part of Orissa was persistently an area of low pressure, more especially during the summer monsoon. In 1871 a similar tendency was exhibited in Orissa and the north-eastern part of the Bay; but in the north-west of the Bay, the pressure was relatively higher; and, in 1872, a relative depression appeared in the upper part of the Ganges valley and the Province of Oudh, and lasted up to the close of the monsoon of 1873. There can hardly be a doubt that these protracted variations, (which nevertheless are distinctive of particular years and are not recurrent,) are closely connected with those variations of the winds and of the rainfall which characterise the seasons of different years. Hitherto it has been possible to establish their existence, only in some parts of Bengal and the North-Western Provinces; but now that the Punjab, Rájputána, and other parts of India are equally available for comparison, it may be expected that the study of these protracted variations will throw much light on the causes of drought and floods, and may even render it possible, to some extent, to forecast the seasons.

Note on the calculated elevation of the neutral plane of pressure.

The calculation of the elevations in the last column of the table on page 175, has been made on the basis of the law, discovered by Sir John Herschell, (Meteorology, p. 132,) that, for great heights, the relations of the temperature to the pressure are expressed by a parabolic curve. The temperature t for pressure p at the elevation of the neutral plane, is found by the formula

$$t = a + \beta p + \gamma p^2$$

in which the constants a, β, γ, have to be determined. To do this fully, requires at least three corresponding values of t and p to be known. But Sir John Herschell showed that a may also be found by the equation

$$a = \frac{T}{2} - 119\tfrac{1}{2} \text{ Fahr.}$$

when T is the temperature at the lowest station. This being obtained, the two corresponding values of t and p furnished by the either pair of plains and hill stations, suffice for determining β and γ.

Having thus found t at the elevation of the neutral plane, the following formula gives the elevation required—

$$x = h\left\{(1 + 0{\cdot}00366\, a) \log \frac{P}{p} + 0{\cdot}000795 \left\{ (T - t) + \beta\,(P - p) \right\} \right\}$$

wherein $h = 60{,}309$ feet, (when common logarithms are used) and a and β, T and t, are converted into centigrade degrees and temperatures.

P and p are the pressures at the sea-level and in the neutral plane respectively.

The heights were computed separately for each pair of stations with the following results:—

	Sikkim.	Ceylon.
November	19,472 feet.	19,684 feet.
December	9,076 „	9,226 „
January	5,905 „	5,978 „
February	3,502 „	3,539 „
May	11,755 „	11,965 „
June	12,123 „	12,300 „
July	10,822 „	10,983 „
August	9,432 „	9,570 „
September	7,465 „	7,612 „

HYGROMETRY, CLOUD AND RAINFALL.

102. The potential energy of vapour.—The all-important functions discharged by the vapour of the atmosphere, in setting up convection currents, and thereby causing winds (§ 33); in tempering the extremes both of heat and cold; in transporting water to elevations, whence it can flow down over the land, rendering it habitable while ever abrading its surface,—depend on the fact that, in the act of evaporation, it locks up a store of potential energy, its so called latent heat,[1] which it transports, without loss or waste, to distant regions; and then, on the lowering of its temperature, again sets it free as heat, while the vapour returns to a liquid or solid state. Espy, and, at a quite recent date, Loomis, and especially Reye, have luminously insisted on the part which it thus plays in the generation of storms; and although it cannot be said that these views have yet received the general adhesion of meteorologists, no one, I think, who has long observed and considered the atmospheric phenomena of a country such as India, can entertain much doubt as to their eventual triumph. I shall have occasion to recur to this subject when treating of storms; but before attacking these more complex phenomena, we must discuss the conditions under which vapour is absorbed into the atmosphere, and, after a longer or shorter journey through or with its mass, is set free as dew, fog, cloud, rain or other form of atmospheric precipitation.

103. Sources of vapour.—The general conditions which determine evaporation have already been described in the introductory chapter of this work. It goes on at all temperatures, wherever a moist surface is exposed to the action of non-saturated air; not only from the sea and other expanses of salt or fresh water, but from the leaves of grass and trees, from the ground through which it rises, drawn up by capillary attraction from the damp substrata; nay, in certain arid states of the atmosphere, from organic and non-organic substances which appear dry to the touch, but which, nevertheless, though the air may be far below saturation, contain certain small quantities of absorbed moisture. Every chemist knows that his filter paper and most of the powders that he has to deal with in the processes of chemical analysis,

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[1] The term "latent heat," originally proposed by Black, has become so widely used, that its abandonment would now be attended with much difficulty. But *latent heat* is no more *heat* than is the momentum of a moving railway train, or the potential combustion of an unignited lucifer match. Instead of being set free as heat, it may become momentum, and before being absorbed by the evaporating water, it may have been stored up for ages as a bed of coal.

must be exposed for a time to the temperature of boiling water, in order to free them from that moisture which otherwise adheres to them, and renders their weight excessive and uncertain; and the brittleness of paper and quill pens, and the warping of wooden articles of household furniture in the dry, hot winds of the interior of India, are familiar instances of the change which such organic substances undergo, when they lose that moisture which ordinarily they hold absorbed. The ocean is, indeed, the principal source of atmospheric vapour; but a large part of the rain, that falls on a land surface, passes again at once into the atmosphere; and, in certain cases, tracts artificially irrigated, may furnish sufficient vapour to yield an occasional shower of rain, where there is no other source of supply.[1]

104. Evaporation in India and on Indian seas.—What may be the average quantity of vapour that passes into the atmosphere in the course of a day, from a constant water surface, is a subject on which information is at present very scanty. This arises not so much from any want of appreciation of its intrinsic importance, as one of the data of meteorology, as from the difficulty of the experimental enquiry. Observations on the evaporation that takes place from a vessel of water, freely exposed to the atmosphere, have frequently been made; and would have been still more general, but that there is extreme uncertainty how far the results represent the evaporation from broad water surfaces, and, *à fortiori*, from any given land surface. The following are a few of the results hitherto recorded in India.

In 1844,[2] Mr. Laidlay found that, in the months of October and November, during a voyage from England to Calcutta, the evaporation from the moist surface of a porous wooden plug which closed the bottom of a tube of water, suspended in the shade, amounted, on an average, to 0·9 inch per day between the equator and the Sandheads; and the same instrument, suspended in the shade in an open verandah in Calcutta, during a year, and observed daily, gave the following daily average in each month:—

January ...	...	0·537 inch.	July ...	...	0·358 inch.
February...	...	0·695 „	August ...	...	0·315 „
March ...	...	0·714 „	September	...	0·373 „
April ...	...	0·602 „	October ...	...	0·315 „
May ...	...	0·650 „	November	...	0·565 „
June ...	...	0·494 „	December	...	0·468 „

Year 0·507 inch.

[1] See the Meteorology and Climate of Káshghár and Yárkand. Indian Meteorological Memoirs, Vol. I, page 59.

[2] Journal of the Asiatic Society of Bengal, Vol. XIV, Part I, page 215.

That the evaporation at sea should so much exceed that on land, can only be explained, by inferring that the instrument was sheltered from the wind in the verandah, much more than on board the ship.

A far more extensive series of observations was made by Mr. T. G. Taylor at the Madras Observatory, between 1830 and 1843. The evaporation observed was from a cylindrical copper vessel, freely exposed to the sky; and the evaporation was noted from week to week. Mr. Taylor observes that the evaporation was enhanced by the action of the sun on the metal sides of the vessel; but that, on the other hand, on most days, the water was somewhat protected from the wind by the edges of the cylinder. The mean daily evaporation, found during the 13 years, was as follows :—

January	0·300 inch.	July	0·413 inch.
February	0·305 „	August	0·354 „
March	0·359 „	September ...	0·334 „
April	0·392 „	October	0·288 „
May	0·460 „	November ...	0·247 „
June	0·484 „	December ...	0·266 „

Year 0·350 inch.

Lieutenant Ludlow found, by comparative experiments on the edge of the Red Hill Tank, with a vessel similar to the above, and also on the surface of the tank, that the ratio of the evaporation from the latter to that on the former was as 10 to 14. This would give an annual average for the water surface of 0·25, or ¼ inch per day. This result is therefore much below that obtained by Mr. Laidlay in Calcutta, and still more below that at sea. But still lower results were found by Mr. A. R. Binnie, C.E., on the large Ambajhári tank at Nágpúr; and the observations, though indirect, are probably more truly representative of the evaporation of sheets of water, than those made with small vessels, as in the experiments previously described. During the dry season of 242 days, betweeen the 10th October 1872 and the 9th June 1873, the total loss of water, from all causes, was a depth of 7 feet, or 0·347 inch per day, on an average. Deducting the quantity drawn off for use and lost by leakage, and adding the small rainfall, Mr. Binnie finds that the average evaporation was probably 0·198 or ⅕ inch per day. But the climate of Nagpur, during the six or eight months to which Mr. Binnie's calculations refer, is one of great dryness; and we should in all probability err on the side of excess, were we to take the evaporation of the Ambajhári tank, as representing that of the ocean. Mr. L. D'A. Jackson, in his recent work on the "Hydraulic Statistics of India," mentions that the evaporation of the Vehar tank, to the north of Bombay, had been found by Mr. Conybeare to be only ⅛ inch daily. If, therefore, for the seas around India, we assume $\frac{1}{10}$ inch

daily, we shall probably make a safer, but perhaps still a liberal estimate. At this rate, the total evaporation would amount to 282,320 cubic feet per square statute mile of sea surface daily; and since, at the temperature of 80°, one cubic foot of pure water weighs lbs. 62·3074, avoirdupois, the weight of water evaporated from each square mile daily, will be, in round figures, 14,475,000 lbs., requiring, at 80° Fahr., the absorption of 7,975,725,000 units of heat (§ 19). When we consider that each unit of heat, thus locked up, is potentially equal to lifting a pound weight of the atmosphere through 772 feet, against gravity (§ 28), we may form some vague conception of the enormous quantity of energy which thus passes into the atmosphere, and may become kinetic on the condensation of the vapour.

105. Quantity of vapour in atmosphere. Absolute humidity.—The vapour that passes into the atmosphere, by evaporation from a land or water surface, is gradually dispersed through it by upward diffusion (§ 12), the rate of which increases as the square of the absolute temperature.* But the process is a slow one, owing to the molecular friction of the vapour against the air through which it makes its way. The rate given by Professor Stephan's calculation, based on the results of Professor Loschmidt's experiments, has been already given in § 12.

In India, the proportion of water vapour in the atmosphere, at the land surface, is very variable. Its weight or mass, in proportion to that of the dry air with which it is intermingled, is readily calculated from its tension e and the total pressure of the atmosphere at the time p, by the formula, $\frac{\cdot 613\, e}{p-e}$; and the weight, in grains, per cubic foot of air may be ascertained from Table XII of the accompanying Tables of reduction, taking the temperature and the elastic pressure as arguments.

On the Házáribágh plateau, during the prevalence of the hot land-winds, the quantity is sometimes as low as $\frac{1}{260}$ of the mass of the atmosphere, or about 1·7 grains in the cubic foot of air; and in the neighbourhood of the coast, during the rains, it occasionally exceeds $\frac{1}{50}$, or upwards of 11 grains to the cubic foot. The tension varies from about 0·05 to 1·15 inch.

106. Variation of absolute humidity with elevation.—We have seen in the first chapter (§ 13) that the vapour which originally is absorbed by the lowest stratum of the atmosphere, tends to diffuse upwards, until the distribution shall be the same as if no air were present. If the temperature of this vapour atmosphere were uniform throughout, this final or limiting condition would be such, that the logarithm of the pressure would decrease in a simple ratio of the height, and the vertical thickness of the vapour atmosphere would be about $1\frac{2}{3}$ times

as great as that of air. But this final condition can never be attained. In the case of air, the diminution of temperature only renders the higher strata more dense than they would be with an uniform temperature; but in the case of vapour, it brings about condensation, and thus renders the atmosphere a still, on an enormous scale; the sun's rays and the watery surfaces of the earth being respectively the fire and boiler, and the cloud-bearing strata, which are cooled by radiation and convection, the representatives of the condenser. The following table will serve to illustrate this fact. The first and fourth columns give the means of the observed vapour tensions at Goalpara and Roorkee, in each month of the year; the second and fifth the hypothetical corresponding tensions at the elevations of Darjeeling and Ranikhet respectively, computed according to the barometric law, for the actual temperatures; but substituting for the height of a homogeneous atmosphere of air in the barometric formula that of a homogeneous atmosphere of vapour; and the third and sixth columns the mean tension of the vapour at the two hill stations as deduced from the observations of the psychrometer. The two final columns shew the tension of saturated vapour at the mean temperatures of the two hill stations. The true mean tension of saturation, deduced from the individual temperature observations, would be a little higher.

MONTH.	Goalpara, 5 years.	DARJEELING, 6 YEARS.		Roorkee, 3 years.	RANIKHET, 3 YEARS.		TENSION OF SATURATION.	
		Comp.	Obs.		Comp.	Obs.	Darjeeling	Ranikhet.
January ...	·432	·369	·206	·282	·244	·167	·273	·317
February ...	·453	·387	·224	·307	·267	·188	·297	·345
March ...	·501	·429	·252	·367	·320	·214	·372	·457
April ...	·650	·558	·334	·372	·326	·236	·451	·686
May ...	·785	·674	·423	·473	·415	·316	·520	·735
June ...	·903	·776	·525	·721	·632	·480	·578	·776
July ...	·926	796	·543	·914	·801	·581	·595	·703
August ...	·931	·800	·545	·905	·793	·567	·595	·663
September ...	·901	·774	·506	·827	·724	·516	·557	·638
October ...	·794	·681	·365	·560	·499	·331	·475	·540
November ...	·608	·521	·264	·383	·341	·239	·368	·434
December ...	·473	·409	·210	·318	·283	·193	·296	·372
Year ...	·696	·598	·366	·536	·470	·336	·448	·555

Both Darjeeling and Ranikhet are situated at some miles distance from the plains, and therefore do not exactly represent the state of the atmosphere, at their respective elevations, vertically above Goalpara and Roorkee; but assuming that they approximately represent that condition, it follows from the above tabular statement, that the quantity of vapour in the atmosphere at these heights, is little more than from three-fifths to two-thirds of that which would result from vertical diffusion indefinitely prolonged, and were the temperatures such as

to admit of this diffusion without condensation. The difference must represent the quantity of vapour condensed in the atmospheric strata between the two stations, or otherwise removed; and also the permanent retardation in the diffusion, which is brought about by condensation as cloud, &c., and re-evaporation.

The cloud stratum first formed, again evaporates from its upper surface under the sun's rays, and frequently a second condensation takes place at a greater height, forming a second layer of clouds; so that the actual vertical distribution is very irregular, and it is further complicated by the prevalence of different wind currents at different heights, some of which contain more vapour than others which have a different origin. But the general result is, that the decrease of vapour tension is much more rapid than even that of the air with which it is intermingled, and that more than three-fourths of the whole vapour of the atmosphere is restricted to heights below 20,000 feet.

107. Geographical variation of absolute humidity.—The quantity of vapour in the air at any place is, of course, mainly dependent on its distance from the sea, and upon the direction of the wind; partly also on the temperature, since, the higher the temperature, the greater the quantity of vapour that can exist in a given volume. As a general rule, therefore, the interior of India, and more especially the Upper Provinces, has a smaller quantity of vapour in the air than places situated on and near the coast line; but if the prevailing direction of the wind is from the land, and that land be dry and heated, places situated almost on the coast line may have an extremely dry atmosphere. Such is the case at Madras during the prevalence of the land winds, and also on the coast of Sind and the Mekran. The most persistently humid regions within our area, are the west coast of Ceylon and Travancore, and such islands as the Andamans and Nicobars; which, being near the seat of the highest mean yearly temperature, are, at the same time, sea coasts, where the prevailing winds are those from the sea.

Generally, in the interior of India, and, indeed, throughout Northern India, there is a very great variation in the proportion of vapour in the air at different times of year; and, in such cases, the variation depends on the annual change of wind direction. This change is particularly abrupt and striking in the Central Provinces and Berar, and in the higher part of the N.-W. Provinces; where the intensely hot and dry season of May is rapidly succeeded by heavy rain and a great fall of temperature, on the land winds giving way to those from the sea. The following are fair examples of these several phases of climate: Colombo, Galle, and the Nicobars represent an uniformly humid

climate with a high temperature; Mooltan and Dera Ishmail Khan an uniformly dry climate; Calcutta and Berhampore one in which the change from drought to dampness is gradual; and Nagpur and Roorkee one where it is sudden and strongly contrasted. The absolute humidity is shewn in two forms; in the first table, by the mean vapour tension of each month; and in the second, by the weight in grains of vapour in each cubic foot of air.

Monthly mean vapour tension at ten Stations.

MONTHS.	HUMID.			ARID.		CHANGE GRADUAL.		CHANGE ABRUPT.	
	Colombo.	Galle.	Nicobars, Day obs.	Mooltan.	Dera Ishmail Khan.	Calcutta.	Berhampore.	Nagpore.	Roorkee.
Years ...	6	7	4	2	2	7	5	2	7
January ...	·802	·815	·814	·226	·192	·470	·410	·318	·288
February ...	·807	·837	·783	·285	·238	·551	·428	·310	·329
March ...	·864	·868	805	·342	·311	·682	·502	·297	·347
April ...	·917	·901	·839	·335	·297	·856	·744	·292	·340
May ...	·918	·919	·885	·437	·389	·935	·843	·354	·430
June ...	·912	·921	·898	·596	·538	·996	·974	·668	·704
July ..	·887	·906	·880	·820	·862	1·004	·991	·790	·896
August ...	·870	·896	·842	·821	·835	1·005	·988	·774	·896
September ...	·871	·920	·854	·753	·713	·989	·962	·746	·815
October ...	·864	·903	·853	·497	·473	·865	·804	·524	·514
November ...	·842	·876	·840	·354	·349	·628	·581	·345	·329
December ...	·820	·849	·812	·291	·268	·479	·443	·330	·290
Year ...	·865	·884	·842	·480	·455	·788	·722	·479	·515

Monthly mean weight of vapour (grains) in one cubic foot of air.

MONTHS.	HUMID.			ARID.		CHANGE GRADUAL.		CHANGE ABRUPT.	
	Colombo.	Galle.	Nicobars.	Mooltan.	Dera Ishmail Khan.	Calcutta.	Berhampore.	Nagpore.	Roorkee.
January ...	8·52	8·69	8·68	2·52	2·16	5·10	4·48	3·45	3·20
February ...	8·57	8·89	8·32	3·16	2·66	5·93	4·64	3·33	3 62
March ...	9·14	9·20	8·53	3·68	3·40	7·23	5·35	3·14	3·74
April ...	9·68	9·53	8·90	3·54	3·16	9·01	7·82	3 05	3·59
May ...	9·69	9·73	9·40	4·55	4·09	9·82	8·84	3·66	4·49
June ...	9 65	9·76	9·54	6·17	5·59	10·48	10·24	7 01	7·33
July ...	9·40	9 62	9·36	8·52	8·95	10·58	10·45	8·41	9·44
August ...	9·23	9·51	8·96	8·59	8·72	10·61	10·43	8·24	9·45
September ...	9·24	9·77	9·08	7·90	7·52	10·45	10·15	7·96	8·63
October ...	9 16	9·59	9·09	5·31	5·09	9·15	8·52	5·59	5 50
November ...	8 94	9·52	8·96	3·84	3·84	6·74	6·24	3·72	3·60
December ...	8·71	9·04	8·66	3·23	2·99	5·20	4·82	3·58	3·22
Year ...	9·16	9·39	8·96	5·08	4·80	8·36	7·66	5·09	5·48

The annual average vapour tension on the coast may be taken at 0·8 inch, being rather higher in the south than the north, on west than on east coasts; and the average of the drier stations in the interior at 0·5 inch. But no meteorological element is more subject to variation with purely local conditions, than the vapour tension of the air. A broad river, an expanse of irrigated fields in one or more directions around a station, will altogether change the character of the winds blowing over it; and thus the humidity of neighbouring stations may be very different, owing to such peculiarities of the *entourage*.

Stations situated on plateaux, such as Házáribágh, Seoni, Saugor, and Rawalpindi, generally enjoy a dry atmosphere; which may be attributed, partly to the comparative absence of local evaporation, partly to their elevation, which brings them within the sweep of a stratum of the atmosphere, of much lower absolute humidity than that which rests immediately on the lower plains.

108. Annual variation of absolute humidity.—The very great contrast between the absolute quantities of vapour in the air in the winter and summer, which characterises the atmosphere of Northern India, in common with that of other monsoon regions, depends on the fact, that all the conditions enumerated in the preceding section, (of course with the exception of invariable geographical position,) are in general in favour of dryness, in the winter; in favour of dampness, in the summer monsoon. At the former period, the wind blows from the land, and the temperature is low; at the latter, the air is drawn from a great extent of tropical sea, evaporating under a nearly vertical sun; and the absolute humidity of different places is then determined, chiefly by their distance from the sea and by their elevation. In the hot weather, and again in October, the greater prevalence of sea-winds in Bengal (§ 90) and of land-winds in Upper India (§ 93) make the contrast between the maritime and inland tracts very great. Instances of this may be observed in the tables given in the preceding section.

As a general rule, throughout India, the vapour tension is lowest in January, coinciding with the lowest temperature, and, approximately, with the highest pressure at sea-level. At a few places on the sea coast of Bengal and the Northern Circars, and in Orissa, where sea-winds set in very early in the year, it is slightly lower in December; and, indeed, generally in Northern India, there is but little difference between the two months. In Assam, Bengal and Orissa, and on the west coasts of India and Burmah, it rises steadily and rapidly, after January, up to the setting in of the rains; but in the dry tracts of the Upper and Central Provinces, where the land-winds prevail through the spring months, the rise is very slow up to June, and then very sudden. At the end of the summer

monsoon, the fall of tension is almost equally abrupt, and only somewhat less rapid in Bengal; and on the south-west coast of Ceylon it is very small, not exceeding 0·1 inch. Here, and on the coasts of the peninsula, the tension rises from January to April or May; then declines somewhat while the rains are falling in Northern India; and rises again, especially on the east coast, in October, when the rains set in in the Carnatic and Eastern Ceylon.

109. Relative humidity. Geographical and annual variation.—It has been already explained that the relative humidity of the atmosphere or its nearness to saturation, depends, not only on the quantity of vapour present in the air, but also on the temperature, which determines the tension of saturation; and it by no means follows the same law of distribution, either in space or time, as the absolute humidity already treated of; except, indeed, during the rains, and then only in a horizontal direction. In the cold season, more especially after November, the descent of the anti-monsoon (§§ 84, 85), together with the more intense cold of Upper India, brings the atmosphere of that tract nearer to saturation, than that of the maritime belt and the peninsula; and thus, while, in the maritime provinces, there are but one period of annual maximum and one of minimum humidity, in the Punjab and in Central India and the North-Western Provinces, there are two annual maxima and two minima; and, in the drier part of the first-named province, the winter is the dampest season of the year. This is also the case in Europe, and even in Central Asia north of the Himalaya; and, for a similar reason, stations on the coast line have, at all times of the year, a higher degree of relative humidity, than those on the plains of the interior. But the rate of increase is very different at different seasons; and in consequence of the greater cold of upper and extra-tropical India, in the first three months of the year, the rule of increasing dryness with increasing distance from the coast, holds good inland only as far as Behar; and thence to the Punjab, the relative humidity of the atmosphere increases steadily. It appears to be higher also through Central India north of the Satpuras, but the meteorological statistics of this tract have not yet been sufficiently worked out, to enable us to fix the limits of the area of higher winter humidity.

From January to May, and, in the Punjab, up to June, the temperature rises steadily; and we have seen that, as a consequence of this, the sea-winds, which begin on the coasts of Bengal as mere afternoon winds in January, gradually penetrate further and further up the country, introducing vapour, which raises not only the absolute but also the relative humidity of the air. Where they have not yet penetrated, the relative humidity falls lower with the rise of temperature; and thus the annual

period of greatest dryness, at any place, falls the later, the greater its distance from the sea.

At False Point, the driest month is November; at Vizagapatam and Saugor Island, December; at Chittagong, January and February; and at Dacca, February; at Calcutta, Burdwan, Jessore, Berhampore, Silchar and Goalpara, as well as Gya, Patna and Monghyr, the driest month is March; but whereas, at the stations near the coast, February is almost as dry as March, while April has a much higher humidity, the reverse is the case in Behar. On the Gangetic plain, above Behar, and also through Central India, April or April and May are the driest months; and, in the Punjab, May or June.

The summer maximum humidity, in Northern India, occurs everywhere in July or August; in the latter month in the Punjab; and the second minimum falls in November throughout Upper and Central India, coinciding with the highest atmospheric pressure of the year at the elevation of the hill stations. The second or winter maximum of humidity falls in January, throughout the Upper Provinces; in December, in the Central Provinces; but, to the south of the Satpuras, the rise is very slight. We shall presently see that the prevalence of cloud follows a very similar law of variation in Northern India.

In the more southerly part of the peninsula, the annual change of the atmospheric humidity is different on the opposite coasts. On the west coast, for instance, at Colombo, Cochin and Goa, the air is most humid when the summer monsoon is at its height, *viz.*, in June in the south, and July or August at the more northerly stations. But on the east coast, at Trincomalee, Negapatam, Madras and Vizagapatam, the greatest humidity falls in September or October at the more northerly, in November at the more southerly stations; being determined by the retroversion of the autumn monsoon towards the Carnatic. The most humid season in Madras, therefore, coincides with the first period of minimum humidity in Upper India.

110. Vertical variation of relative humidity.—From what has been said of the tendency of vapour to diffuse upwards, and of the effect of the decreasing temperature, which compels condensation before the condition of equilibrium can be attained, it follows that, for a certain distance above the earth's surface, the relative humidity of the air will, in general, increase with the increasing elevation. The observations made in balloon ascents, as, for instance, by Mr. Walsh and Mr. Glaisher, shew that this is the case; and the same fact is further illustrated by the higher humidity of the atmosphere at the hill stations of India, as compared with those on the plains. But this increase does not go on indefinitely. At a certain elevation, which varies with the absolute

humidity of the air, and also with the temperature, saturation is reached; and a part of the vapour is condensed as cloud, in which state, diffusion is stayed, until the cloud is evaporated under the sun's rays.

What, indeed, might be the final condition of the atmosphere if it were motionless, if saturated air were never to flow away towards cooler regions, and to be replaced by inflowing and descending currents of drier air, it is somewhat difficult to realise; and the speculation is without practical application. But we have a very important practical illustration of what takes place over tropical seas, when the generated vapour is not carried away by lateral currents, *viz.*, in the belt of calms and heavy rains over the Atlantic, and in the conditions which precede the formation of cyclones in the Bay of Bengal and other seas, sufficiently distant from the equator to allow of the operation of Ferrel's law. Of these conditions I shall speak presently in more detail. At present, it suffices to remark that these are tracts of heavy rainfall, chiefly diurnal in the belt of calms, but continuous and increasing in the cyclone cradle.

At the elevation of the hill stations of India, the air has, as a general rule, a higher relative humidity than on the plains; and in the rains, and, not infrequently, also in the first months of the year, is at saturation; the hill tops being enveloped in cloud. But at certain times of the year the relative humidity of these elevations is lower than on the plains. The following table of the mean relative humidity at certain hill stations both in the Himálaya and to the south, together with that of neighbouring stations at low levels, will serve to shew the average difference in different months of the year:—

Months.	N. W. Himalaya.		E. Himalaya.		Cl. India.		Nilgiris.		Ceylon.	
	Roorkee, 5 years.	Chakrata, 5 years.	Goalpara, 5 years.	Darjeeling, 6 years.	Hoshangabad, 3 years.	Pachmarhi, 3 years.	Coimbatore, 1-2 years.	Wellington, 1-2 years.	Colombo, 5 years.	Newara Eliya, 5 years.
January...	66	73	72	76	34	37	59	70	79	77
February	63	67	65	77	34	31	52	57	78	69
March ...	49	59	61	68	21	21	59	61	79	71
April ...	40	49	73	75	15	15	63	62	80	78
May ...	45	57	79	81	19	22	71	72	81	82
June ...	60	77	88	90	43	54	71	74	85	88
July ...	78	93	86	91	81	91	75	74	84	87
August ...	79	94	86	92	80	89	75	74	83	82
September	75	89	87	90	76	85	71	73	82	85
October...	65	63	81	77	44	48	79	82	83	87
November	57	40	77	72	35	33	72	83	82	83
December	64	48	75	71	38	39	69	72	81	83
Year	62	67	77	80	43	47	68	71	81	81

N. B.—In the first four columns and the sixth and seventh, the means are those of the 24 hours approximately. In the case of the other stations those of the day-time (10 A.M. and 4 P.M.) only.

This table shews that, at the Himálayan stations, the only season at which the relative humidity at 6,000 or 7,000 feet is lower than on

the plains, is the last three months of the year; when the air resting on the plains is cooled by radiation under a cloudless sky, and the anti-monsoon from the southern seas has not yet set in. The sudden rise and high degree of humidity in January at Chakráta, which may be taken as representing the North-west Himálaya generally, is very striking. In the Central Provinces, the average of three years shews a slightly higher humidity at 3,000 feet in December and January; but in the earlier and later months of the dry weather, there is but little difference between the hills and plains, the dryness of both being excessive; more especially in April, when the average of the 10 A.M. and 4 P.M. observations does not exceed 15 per cent. In the rains, the rule is the same as in the case of the Himálaya and damp climates generally. At Wellington, on the eastern slope of the Nilgiri plateau, the relative humidity (on the average of one and a half years) appears to be higher than on the plains at the eastern foot of the hills at all times of the year, excepting in April, July and August, and the winter maximum of humidity is as strongly marked as in the Himálaya. But at Newara Eliya the humidity (of the day-time) is lower than that of Colombo from January to April, and especially in February and March.

111. Formation of cloud.—The clouds of the lower atmosphere *viz.*, *cumulus* and *pallio cumulus*, are produced, as indeed is shewn in their forms, by the dynamic cooling and condensation of ascending vapour. The characteristic forms of cumulus clouds may be imitated by dropping milk gently into a tumbler partly filled with water. In this case, as a heavier fluid is introduced into one specifically lighter, the rounded contours are directed downwards; whereas cumulus cloud being produced by the introduction of a less dense fluid from below, the rounded contours are directed upwards. The flat base of the cumulus is the plane at which condensation begins, and the summit of the ascending air column is thereby rendered visible.

The height at which these clouds form varies with the relative humidity of the air, being of course the lower, the greater the humidity, as already explained in § 110. In nor'-westers the *pallio cumulus* is sometimes barely 1,000 feet above the land surface. But in fine spring weather, the *cumulus* clouds ordinarily form at from 3,000 to 6,000 feet.

A mass of cumulus cloud, as Espy pointed out, is the seat of a local convection current; and this fact explains the rapid upward growth of cumulus, which far exceeds the rate at which water vapour is diffused through the air. No sooner is a tuft of cumulus formed, than, in that little mass of air, a differential decrement of temperature is established, as compared with that of the clear stratum around, and the air of the lower

strata sets towards it, as represented in the accompanying diagram, Fig. 13, copied from Espy's work. The higher clouds, such as *cirrus* and *cirro-stratus*, appear to depend on the existence, at a great height, of a current of air from some southerly direction; and the cooling which determines the formation of cloud, may be due to internal movements, which is probably the case with cirrus cloud; or to radiation, and in certain cases, possibly, to the intermingling of nearly saturated air masses at different temperatures.

Fig. 13.

In the winter season, after the interval of fine clear weather which prevails when the rains have ceased, the appearance of cirrus wisps at very great elevations, is the first harbinger of the anti-monsoon. This is followed by a sheet of cirro-stratus at a much lower level, and eventually by pallio-cumulus, but the height of the rain-cloud appears to be much greater at this season than during the hot weather and rains.

112. Annual and geographical variation of cloud distribution.—The relative prevalence of cloud follows, of necessity, the same law of variation, as the relative humidity of the higher strata of the atmosphere; and, as the facts given in § 16, and the table on page 205 shew, this, although not identical with the course of variation near the ground surface, at least in magnitude, generally coincides with the latter as regards the annual period of increase and decrease. From a geographical point of view, moreover, those parts of India where the surface atmosphere is driest, are also those where the cloud proportion is lowest. Excluding Sind and Western Rájpútána, for which we have at present no available data, Mooltan and Dera Ishmail Khan, in the driest part of the Punjab, are the stations at which the skies shew the lowest proportion of cloud, *viz.*, 17·4 and 20 per cent. respectiveely, on the average of four years; Lahore and Amritsar are respectively 25·5 and 24·1 per cent.; Roorkee 30·6; Lucknow 37·2; Patna 40·1; and Berhampore 49·6; which is as high as any station in Lower Bengal, but is surpassed apparently by Sibsagor in Upper Assam. The greatest cloudiness is shewn by the Ceylon stations, especially those on the south and west coast of the island. On the mean of from 5 to 7 years, Hambantota shews 70·6, Galle 68·4

and Colombo 60 per cent. of cloudy sky in the day-time. Port Blair on the average of 7 years shews 43·7 per cent of diurnal cloud.

In Northern India, there are two annual periods of minimum and two of maximum cloudiness; the latter corresponding to the summer monsoon and the winter anti-monsoon, respectively. In Southern India, there is but one well-marked minimum, *viz.*, in February or March. In all parts of India, with the exception of the drier tracts of the Punjab, the most cloudy season is the beginning of the summer monsoon; either in June or July. Only at Mooltan and Lahore, is the cloudiness of January slightly the greater. At the close of the rains, the skies of the Punjab become almost cloudless; allowing, as was remarked in §§ 57 and 87, of that free radiation and rapid cooling, which speedily make this province the seat of the lowest temperature and the highest pressure in India. October is here the month of greatest serenity, the average proportion of cloud over the plains being not more than 5 per cent. In November it increases, and reaches a maximum in January and February; after which it diminishes again till May or June. In the North-Western Provinces, especially the lower part, and in Behar, November is a clearer month than October, and the second minimum varies between March and May: and in Lower Bengal, the chief minimum of cloud falls in December, and a second ill-defined minimum in February. In the South, as has been remarked above, February is the month of minimum cloud.

113. Causes of geographical and annual variation.—Somewhat has already been said in explanation of the varying humidity of the different seasons; and this may be generalised in the statement, that over the whole of India, the summer maximum of cloud and relative humidity depends on the monsoon of that season, while the winter maximum of Northern India depends on the anti-monsoon. The former, as we have seen, reaches India in two branches, one of which sweeps across the peninsula and Rájputána from the Arabian Sea; while the other prevails over Bengál, Assam, Burmah, and also in the opposite direction up the Gangetic Valley; which last, however, it shares with the western branch. Now, as both these currents are, in their origin, westerly or south-westerly, they bring vapour most copiously to the west coasts of the two peninsulas; and these coasts are on the average of the year, and especially during the summer monsoon, the most humid regions. In both cases, a considerable range of hills runs parallel with the coast at no great distance inland, and as these hills cause a great condensation of vapour, and, at the same time, in some degree, divert the course of the currents, the narrow coast plain and the western slopes of the hills form a belt of extreme humidity, and the countries beyond the hills to the eastward are much drier. The hills and enclosed plains of Eastern

Bengal and Assam are almost as fully exposed to the south-west monsoon as is the coast of Arakan, and their humidity is equally high. The driest time of year on the Arakan coast is February and March; this is at least a couple of months later than on the coast of Orissa; and is to be explained by the fact, that northerly winds prevail down the Arakan coast during the early months of the year, while southerly winds predominate in the west of the Bay. These, again, are the local phases of the anti-cyclonic circulation of the winds of the Bay, arising from the distribution of pressures, described in § 87.

The plains along the east coast of the peninsula and the plateaux of the interior are extremely dry during the early months of the year; since the temperature is high, while the sea winds of the Bay of Bengal blow along the coast and parallel to it, and, even as diurnal winds, penetrate but a short distance from the sea; while, on the other hand, those from the Arabian sea are stopped by the western ghâts. It has already been explained in § 109, that the most humid season of this part of the peninsula is the end of the summer monsoon; when the winds from the Bay of Bengal re-curve and become easterly, being drawn towards the region of low pressure in the Carnatic. In Central India, again, where north-westerly land winds prevail up to the end of May, winds which come from the arid region of Western Rájpútána, the atmosphere is one of extreme dryness; until, by a shift of wind a few points to the south, the country is brought within the influence of the vapour-loaded current from the Arabian Sea. This has indeed, in part, to surmount the ghâts, but it also blows up the wide valley of the Taptee, and the narrower valley of the Nerbudda; and thus the dry season is suddenly succeeded by one of high humidity (§§ 107, 108). A similar change of conditions affects the plateaux north of the Satpuras, up to the confines of the Gangetic plain.

In this plain, or at least in its lower part, the change from dryness to dampness takes place earlier, and is less abrupt, owing to the gradual advance of the sea winds inland. Thus, Northern Bengal and the eastern part of Behar receive a certain amount of vapour in April and May, which preserves them from that excessive dryness that characterises the plateaux of Central India and the Nerbudda valley. Such is the case on the average; but, at certain times, the dryness of the atmosphere, at Házáribágh for instance, is excessive, and as great as that of any station in Central India. Western Rájpútána, Sind and the Punjab, owe their extreme dryness to their geographical position. When, under the prolonged heating of April, May and June, the Punjab becomes the seat of a barometric minimum, and therefore (§§ 75, 76,) of a cyclonic circulation of the winds, those currents which prevail on the west and south are drawn from the desert tracts of Báluchistán and Persia, or

from the valleys of the surrounding hills. Even to the eastward, these dry winds are still very prevalent; and the summer monsoon of the Arabian Sea being about due west, but little of its saturated air ever passes over the country lying to the west of the Aravalis. It is chiefly on the northern border, that the Punjab is reached by currents that have been drawn from the Arabian Sea or the Bay of Bengal; and then only after traversing more than 1,000 miles of land.

In the winter, however, the Punjab, in virtue of its more northerly position and the rapid clearing of its skies, is subject to a more copious condensation of the lower atmosphere; consequently, a general sinking of the isobaric planes of the higher atmosphere, of which we have evidence in the pressure registers of Simla, Chakráta, &c.; and eventually, an inflow of vapour-bearing air (the anti-monsoon). Until this current sets in, the plains have a higher humidity than the hill stations: for the evaporation from the plains is considerable, while the temperature, and therefore the tension of saturation, is falling more rapidly than in the higher strata of the atmosphere. But no sooner is the anti-monsoon established down to the plains, than upward diffusion brings about saturation of the more elevated strata, and the formation of cloud, together with the winter rains, which will presently be noticed.

114. Relations of humidity and cloud to temperature.—These may be regarded from two points of view, both of which are of high importance. I will, in the first instance, notice the relations of these two elements to the surface temperature; and afterwards, with reference to its vertical distribution, which is of importance in connection with the local pressure of the atmosphere. The result of the discussion in § 25 would lead us to expect that, while a high relative humidity and the prevalence of cloud would influence the mean temperature of the atmosphere but slightly, but would on the whole somewhat lower it, it would very much reduce the range: in other words, the difference between night and day, and to a certain extent also the difference between summer and winter. And a comparison of the tables given at the end of this treatise, and of the facts of which a condensed statement has been given in §§ 67, 109, 112, fully bear out this conclusion. The drier part of the Punjab, and, to a somewhat less extent, the equally arid, but more southerly region about the lower Indus, are the seat of the greatest diurnal range of temperature; whereas Assam and Cachar, which lie under about the same latitude as Sind, but have a damp climate at all times of the year, have the comparatively moderate range shewn in the subjoined table. In the absence of any sufficient data from stations in Western India, I give, for comparison with the above, the corresponding data of Ajmere and Jhansi, which are under about the same

latitude as Sibsagor, Goalpara and Silchar, and which are in a less arid climate than that of Sind.

Stations.	Number of years.	Absolute annual temperature range.	Temperature range on mean of months.	Mean daily range.	Mean temperature.
Sibsagor ...	2	56·0	28·0	14·7	72·0
Goalpara ...	3	52·9	20·8	17·0	74·5
Silchar ...	3	53·3	20·8	17·8	75·8
Jhansi ...	2	76·5	32·8	23·2	78·8
Ajmere ...	2	83·0	33·7	25·7	76·8

Allowing for the differences of elevation, there is then an average increase of 6° or 7° in the mean annual temperature between Assam and Cachar and that part of Central India which is under the same latitude. This must be attributed partly to the greater cloudiness of the Eastern Provinces, but probably more to evaporation, which is only indirectly an effect of the more humid climate. The more contracted temperature range of these provinces is, however, to be attributed mainly to the higher humidity of the air and the more abundant condensation of cloud, which equally obstructs the solar rays in the day-time and the radiation of dark heat from the earth at night.

115. Relations of vertical distribution of humidity and temperature.—In a paper published in the Philosophical transactions in 1874, it was pointed out that, in the normally damp atmosphere of Lower Assam and the outer Sikkim Himálaya, the decrease of the temperature with elevation appeared to vary nearly as the relative humidity of the atmosphere; since the increment of elevation corresponding to a reduction of 1° temperature varies almost exactly as the relative humidity of the air on the plains (Goalpara). And, indeed, we find, on projecting the annual curves of relative humidity and of cloud variation at that station, that the resulting curves are almost identical with the Darjeeling-Goalpara curve of temperature difference in figure 4 page 57.[1] This is shewn in the annexed figure.

Fig. 14.

[1] In figures 14, 15 and 16, the continuous curve represents the variations of the temperature decrement, or rather that of the elevation-increment corresponding to 1°; the interrupted curve is that of cloud variation; and the dotted curve that of relative humidity at the lower station.

It is further to be observed, that in the North-Western Himálaya, the rapid rise of humidity in June and July is accompanied by a certain increase in the value of the elevation increment that corresponds to a fall of 1°; and Dr. Hann had previously found, on investigating the relations of wind direction to the vertical decrease of temperature in Carinthia, that, other circumstances being equal, this latter is more rapid with north and north-east than with south and south-west winds; and it is well known that, in Europe generally, the former are the drier, the latter the humid winds. It appears, therefore, that one important condition that determines the distribution of temperature in a vertical direction, is the relative humidity of the air; in other words, the tendency of its vapour to condense and form cloud; and this result concides with that of Mr. Glaisher's observations quoted on page 61, and with the conclusions from theory as explained in §§ 31, 32, 33, in the earlier part of this treatise.

But at the close of the rains, in the dry climate of Upper India, the difference of temperature between the hills and plains, instead of increasing, as is the case in the comparatively damp atmosphere of Northern Bengal, falls rapidly to a minimum, while the skies become almost cloudless and the relative humidity of the lower atmosphere also falls. The curves of relative humidity and cloud variation at Roorkee, and that of the increment of elevation corresponding to a fall of 1° between that station and Chakráta, in figure 15, illustrate this relation, and may be contrasted with the curves in the preceding figure. This apparent contradiction of effects is, however, easily reconciled, if we bear in mind the conclusions drawn in § 25 as to the great influence of small quantities of cloud in checking radiation from the earth's surface. In Lower Assam, the average

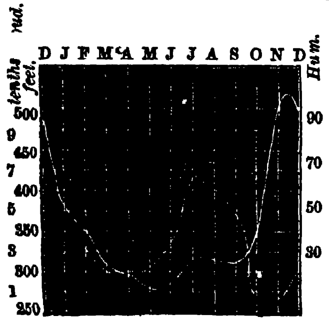

Fig. 15.

of cloud in the most serene month of the year, (November) is 25 per cent.; at Roorkee in October and November it is only between 5 and 6 per cent.; or as we may put it, since these are only average results, the number of cloudless days is four or five times as great at Roorkee as in Lower Assam. This extreme clearness of the skies, at the former place, allows of the land surface and the lower atmosphere in contact with it being cooled rapidly by radiation; and thus brought nearer to the temperature of the higher strata. This is not the case in Assam and Northern Bengal; and there, the chief effect of the decreased humidity is, that less heat is carried from the lower to the higher strata of the atmosphere.

Another case in which the vertical decrement of temperature becomes less rapid as the atmosphere becomes drier, and to such an extent that the annual minimum difference between the temperature of a hill station and the plains nearly coincides with the minimum of cloud and humidity, is afforded by Hoshangabad and Pachmarhi; the curves of humidity and cloudiness as recorded at Hoshangabad, and of the elevation increment corresponding to a fall of 1°, being those shewn in the accompanying figure (fig. 16). But Pachmarhi is only 2,400 feet above the plain of the Nerbudda valley; and, during the dry season, the air is loaded with dust, constituting a haze which extends to a much greater height than the hill station. It is, very probably, the absorption of heat by this dust that renders the summer temperature of Pachmarhi so high relatively to that of the plains.

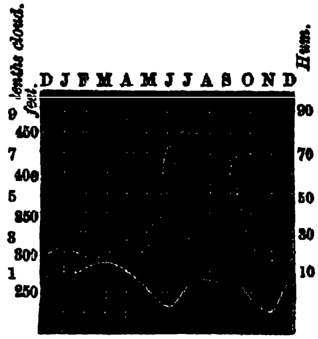

Fig. 16.

116. Conditions that influence rainfall.—To a certain extent, the variation of the rainfall follows the same general laws as the variation of the relative humidity of the air, and of cloud. But rainfall is influenced by other local circumstances, such as the form of the ground; and its copiousness depends, not only on the atmosphere having a high prevalent humidity, but also on the volume of the vapour-loaded air which reaches a place, and, having there condensed and precipitated its vapour, passes on to other regions. The velocity of the saturated current and the amount of cooling it undergoes over a given place, are therefore important factors in the resulting product.

117. The rainfall of Cherra Punji.—The highest precipitation occurs when a saturated current of air at a high temperature is met by a hill range running athwart its course; and the steeper the slope, the greater is the local precipitation. Cherra Punji in the Khasi hills, long renowned as having the highest recorded rainfall in the world, is a remarkable illustration of the combination of these favouring conditions. The Khasi hills rise abruptly from the *jhils* of Silhet, which being but a few feet above sea level, and receiving the copious drainage of the hills that surround Cachar and Silhet, present, during the rainy season, a broad sheet of water, from which emerge a few villages built on mounds and the low ridges locally termed *tilas*. Over this low inundated tract, sweeps the south-west monsoon from the Bay of Bengal; and, meeting the Khasi hills, is abruptly driven up to a height of 4,000 feet, before it resumes its course towards Upper Assam and the Eastern Himálaya. These circumstances alone suffice to produce an

exceptionally heavy rainfall along the face of the range. But Cherra Punji is, in some respects, exceptional, even in this highly humid region. It stands on a little plateau of thick-bedded sandstones, bounded on two sides by precipices of 2,000 feet sheer descent, which close in gorges, debouching southwards on the plains. The south-west wind blows up these as well as on the southern face of the general scarp; and, having reached the heads of the gorges, ascends vertically. Thus Cherra Punji is surrounded, or nearly so, by vertically ascending currents of saturated air; the dynamic cooling of which, is the cause of the enormous precipitation which has made this place famous. It is almost certain that the annual average varies greatly in different parts of the station; although the whole plateau does not cover much more than a couple of square miles. Some of the earlier registers, which were kept at sites near the edges of the plateau, shew a higher precipitation than those kept in recent years at houses nearer its centre.

118. Rainfall of the Western Ghats and Arakan.—Next to the southern face of the Khasi hills, the seats of most abundant rainfall, in the Indian provinces, are the Western Ghâts, Arakan, and perhaps the outer slopes of Sikkim and the Bhootan *doars*. In all these cases, a line of hills runs across the path of the vapour-bearing summer monsoon, forcing the air to rise to some extent, and therefore to undergo dynamic cooling. On the Arakan coast, the rainfall is heaviest in the neighbourhood of Sandoway and Khyook Phyoo, where the hills advance to the coast line; and where, also, the monsoon blows most directly on their face. At the former of these stations, it amounts to about 230 inches, and at Akyab to 205 inches; but to the north of this it diminishes gradually; at Cox's Bazar it is reduced to 141, and at Chittagong to 105 inches. The coast of Tenasserim, (south of the Gulf of Martaban,) has also a very heavy rainfall, not less than that of Sandoway. On the west coast of India, the heaviest rain is on the escarpment of the Ghâts, where they rise abruptly from the Concan. At Mahableshwar it is not less than 260 inches, and at Uttray Mullay, in Travancore, about the same amount. But on the coast line it is less than in Arakan. Thus Bombay has 72 inches, Goa 83 inches, and Colombo 75 inches. Both the Arakan and Malabar coasts receive their rainfall during the south-west monsoon; the northern half of the latter almost exclusively. At Bombay and Goa, rain is extremely rare between October and May; but, on the Arakan coast, the southerly winds continue to bring rain during the prevalence of the Madras monsoon; that is, nearly up to the end of November; and showers fall occasionally in the earlier months of the year. In both cases, the further we go south, the less decided is the distinction of the seasons; and at Galle and Singapore rain occurs more or less at all times of the year.

119. Rainfall of the Dekhan and Mysore plateau, &c.—This region receives its principal rainfall from the west coast; but the air having to surmount the escarpment of the Ghâts before reaching it, that portion which lies immediately to the east of the Ghâts has a very moderate rainfall, and the increase beyond is only gradual. Thus Poona has only 32 inches, Satara 39, Sholapur 28, and Dharwar 37. But Belgaum, which is opposite the low parts of the Ghâts about Vingorla, has as much as 47 inches annually. Bangalore has about 34 and Bellary 17·5 inches. All through the Mahratta country, and as far as Nagpur, the annual distribution of rain is the same as at Bombay, *i. e.*, practically restricted to the season of the summer monsoon. But from Nagpur eastwards, spring storms are not infrequent, and an appreciable amount of rain falls during the earlier months of the year. This augments the total annual fall, so that, at Nagpur, the average is 45 inches, at Raipur and Sambalpur about 50 inches, and at Chanda 48 inches.

120. Rainfall of the Carnatic, Northern Circars, and Orissa.—The rains of the summer monsoon are not much felt on the east coast of the Peninsula, south of the mouths of the Godavari and Kistna. At Madras, the average fall from January to the end of May, is 4½ inches, from June to September inclusive, 15 inches; and it is in October and November more especially, when the southerly monsoon has ceased to blow in Northern India, but re-curves towards the region of low pressure in the Carnatic, that that part of India receives its chief rainfall. The average of these two months is not less than 24 inches, and about 5 inches fall in December. At Vizagapatam, the summer and early autumn rainfall is greater than at Madras, *viz.*, 23 inches, and that of October (10·74 inches) equal to it; but that of November is considerably less, *viz.*, 2 inches only. False Point, again, on the coast of Orissa, has a copious monsoon rainfall, *viz.*, 52 inches in the four months June to September, and not less than 13 inches in October; but in Orissa it is less; and in the hill country to the north, (in Chutia Nagpur) the October rainfall is comparatively small, not exceeding 3 or 4 inches at Házáribágh, Ranchi, and Chaibasa. In all the eastern coast provinces of the Peninsula, showers and little nor'-wester storms (§ 129) occur occasionally in the spring or hot weather months.

121. Rainfall of Bengal and the Gangetic plain.—In Lower Bengal, November, December, and January are comparatively rainless. A late storm sometimes occurs indeed in November; and, in certain years, the cold weather rainfall of Upper India extends down to Bengal, but both are uncertain and perhaps rather exceptional. On the mean of 47 years' registers at Calcutta, December is the most rainless month in the year, as it is that of least cloud. But from this onward, the average

rainfall increases gradually, coming chiefly in the shape of nor'-westers; so that, between January and the end of May, the average fall at Calcutta amounts to 10½ inches, and to 18½ inches at Dacca. This spring rainfall is much more copious in the eastern districts, in Cachar and Assam, than in the western part of the delta. At Silhet, for instance, it amounts to 44·3 inches, at Silchar to 36·5 inches, at Goalpara to 22·1 inches, at Gauhati to 20 inches, and at Sibsagar to 30·5 inches; and it is owing to the frequency of the spring rains, that these provinces are so peculiarly fitted for the cultivation of tea. To the west of the delta and in the North-Western Provinces, rain is less frequent in the spring months, and next to November and December, February and March or March and April are the months of least rainfall, the variation of which therefore coincides with that of relative humidity and average cloudiness (§§ 109, 112). But also, the further we advance to the north-west, the more regular are the rains of the cold season, which, as we have seen, are brought by the anti-monsoon. On the other hand, the setting in of the summer monsoon becomes later and later the further we advance to the north-west, and the total rainfall of that season, and indeed of the year, diminishes, as a general rule, in a like measure. In Lower Bengal, the rains usually set in in June, in the second or third week, though they have been known to begin both much earlier and later. But in the North-Western Provinces, they are hardly looked for before the latter part of the month; and in the Punjab scarcely before July. The decrease in quantity is very marked both from Bengal upwards, and also with the increasing distance from the foot of the Himálaya. Taking a series of stations along the line of the river, we have for the total annual rainfall of Calcutta 66 inches, for Berhampore 53·5 inches, for Bhagalpore 47 inches, for Patna 38½ inches, for Benares about the same, for Allahabad 42 inches, and for Agra 30 inches. The apparent increase about Allahabad may be owing to the imperfect elimination of temporary variations, or to there being an actual increase arising from some local cause. I am inclined to the latter inference. Again, taking series of stations at successively greater distances from the mountains, we have the following:—

Silhet	... 154 inches.	Gorakhpur	... 50 inches.
Mymensing	... 95 "	Benares	... 39 "
Dacca	... 71 "		
		Dehra	... 89
Julpigoree	... 127 "	Roorkee	... 42 "
Dinagepur	... 79 "	Meerut	... 29 "
Malda	... 53 "	Agra	... 30 "

The proximity of the mountains influences the rainfall in various ways; chiefly, perhaps, by causing a certain ascent of the air and dynamic cooling, when the direction of the wind is in the least degree towards the mountains. But they exert other influences also. The temperature of the air falls as we draw near the hills, and its humidity is greater,

partly owing to the hill drainage, partly to the more abundant vegetation of the surface.

122. Rainfall of the Punjab, Rajputana, and Sind.—The eastern part of Rájpútána enjoys a fair share of rainfall in the summer monsoon. Ajmere, for instance, receives about 21 inches in the four months June to September. But the further we proceed west, the scantier is the summer rainfall; while, in the Punjab at least, the winter rainfall, that of the anti-monsoon, becomes more important, both absolutely and relatively; and thus we pass from the conditions of the monsoon region into those characteristic of the temperate zone. At Dera Ishmail Khan, the average rainfall from June to September does not exceed 4·7 inches; while from December to March, it amounts to 2·7 inches; and at Peshawur the former is 5·6 inches, the latter 4 6 inches, on the average of nine years. To the south of the Punjab, in Sind and the Thur desert, neither summer nor winter rains can be said to be regular; and in the latter region, sometimes more than a twelvemonth passes by without a drop of rain. The average annual rainfall of Mooltan and Mozuffergarh is 6 inches only.

123. Barometric changes accompanying rainfall.—Dr. Hann has shewn from the discussion of the rainfall and the hourly barometric observations at Batavia,[1] that falls of rain in the tropics are, as a rule, accompanied by a rise of pressure; and has advanced this fact as an objection to the theory of cyclone-generation advocated by Espy, Reye, Mohn, and the author of this work; which is, that the condensation of the atmospheric vapour as rain and the emission of its latent heat are the immediate cause of the barometric depression in a cyclone, and that by which the disturbance of equilibrium is maintained. The fact that rain is most frequently accompanied by a rise of pressure, is one of familiar experience in Bengal; and Major Godwin-Austen has observed the same phenomenon during the torrential discharges of rain at Cherra Punji. The conditions which precede and accompany rain, in these tropical countries, have only lately attracted special attention, and no satisfactory account of these can at present be given. But some few facts have been lately recorded in connection with this subject, which, at least, seem to throw doubt on the propriety of applying to the case of cyclone-generation, generalizations of an empirical character, which have been drawn from the study of rainfall on the land. As regards the case of cyclones, I reserve the further discussion of this point till it can be taken up in connection with the special description of this class of storms. The following facts have reference to the land rainfall only.

[1] Zeitschrift d. Oesterr Met. Gesell., Vol. IX, p 289.

In treating of those barometric oscillations which accompany rain, we must distinguish between those which progress slowly, covering a period, perhaps, of several days, and those which are sudden and spasmodic, such as precede and accompany nor'-westers and similar squalls. The latter consist of a rapid rise of pressure immediately before the squall, followed generally by a slower fall; and accompanied, as Mr. J. Elliott has lately shewn,[1] by a rapid fall of temperature and vapour tension, an increase in the strength of the wind, and a shift of its direction through a considerable sector of the compass. In two cases described by Mr. J. Elliott, the rise of pressure (which took place during the afternoon, at the time of the normal diurnal fall of the barometric tide,) was such as to render the pressure at 4 P.M. higher than at 10 A.M., and thus apparently to reverse the normal changes of the barometric tide. And in an instance brought to my notice by Colonel Tennant, the barometer rose 0·17 inches from 9h. 30m. A.M. to 11 A.M. (when it is usually falling), and then in the space of 7 minutes fell 0·090, and in the next 27 minutes 0·080. Such oscillations as these can hardly be referred to other than dynamic action; to the movements of the atmosphere, and not merely to changes in its mass. In the case noticed by Colonel Tennant, (as in those described by Mr. Elliott,) the sudden rise of pressure at 9h. 30m. was accompanied by a sudden shift of wind from south-east to north. From this quarter it blew in sharp gusts, as is usually the case in a nor'-wester; having, at 11 A.M., a maximum pressure of 6 or 8 lbs. to the square foot. With the subsidence of its force, the wind veered to north-east, and the fall of pressure took place as above described. More important in connection with the theory of rainfall conditions are those more prolonged gradual oscillations of pressure, which are indicated by the fall of the barometer some days before the advent of rain, and its rise during and after the rainfall. This phenomenon, which is one of constant occurrence in Bengal, has been lately investigated by Mr. J. Elliott in the paper referred to above. He finds, *first*, "that during the rains, the baric differences between the mid-Bay (of Bengal) and the Bengal coast are in a state of continuous oscillation, indicating an action between the Bay and the land, oscillatory, and not constant and continuous in its character: *second*, that an increase of the baric difference above the normal amount is accompanied or followed by the advance of a saturated current from the Bay to the coast: *third*, that this saturated current is determined, from various causes, generally to the north-east, giving the heaviest rainfall to the Arakan coast, and advancing from Akyab northwards; and gradually extending northwards and westwards over Bengal: *fourth*, that the

[1] Indian Meteorological Memoirs, Vol. I, Part 2.

effect of this indraught from the Bay and the condensation over Bengal, is an increase of pressure in Bengal, with usually a very slight decrease in the mid-Bay; or, on the whole, a diminution of the baric difference, followed after a time by a partial or entire cessation of the heavy rainfall."

Some further light is thrown on these oscillations by the daily weather charts of the whole of India, which were prepared to illustrate certain cases of unusually heavy rainfall in the rainy season of 1875.

It appears that, during the rains, a succession of cyclones (or barometric minima) are propagated from Orissa or the north-western corner of the Bay towards Central India and the North-Western Provinces. As shown on the charts, they make their first appearance in this province, being formed there in the quasi-persistent depression which characterises it at that season; and then move to the west or north-west, travelling slowly across the country, with a minimum pressure of perhaps 0·2 below that of Lower Bengal. In the cases discussed, they did not proceed further than Central India or the confines of the Punjab. The winds are higher near the centre than at a distance from it, having in a few cases a velocity as great as 240 miles a day; but in general they are much lower, and they have a higher velocity on the south-west than on the east and north. As these cyclones form and move forward, rain falls more or less heavily in Orissa and Bengal; and, in the intervals, the weather is comparatively fine. For the fuller study of these vortices, a much larger series of daily charts must be prepared and examined than have hitherto been available; but it may be noticed that they seem to throw light on the formation of those more formidable storms which are generated at sea. In certain seasons, cyclones readily recognisable as such by their violence are formed in the northern part of the Bay of Bengal, and it seems a not unreasonable supposition that the former only fail to attain the same strength in consequence, *firstly*, of the condensation being more restricted over the land, and, *secondly*, of the friction which the inequalities of the land surface oppose to the free movement of the winds.

It is further noteworthy that the very heavy rainfall which it was the immediate object of the inquiry to explain, *viz.*, 13 inches in 12 hours at Allahabad in the one case, and 19·5 inches in 24 hours at Delhi in the other, caused a local depression of the barometer; since the pressure was at its minimum during and after the fall. Hence it is to be gathered that even on land, heavy rainfall is sometimes attended by a fall of pressure.

124. Periods of deficient rainfall and famine.—Reference has already been made to Messrs. Meldrum and Lockyer's discovery that

the quantity of the rain that falls on the globe appears to vary proportionally with the abundance of the sun-spots; the greatest rainfall occurring about the period of the sun-spot maximum, and *vice versâ*. Sir William Herschell, and, subsequently, Professor Wolf, have also deduced from old records that, on an average, years of abundant sun-spots appear to be more fruitful and to be characterised by lower prices of cereal produce. In Ceylon this cyclical variation of the rainfall and of cereal abundance appears from the evidence of Mr. Fergusson, the Editor of the *Ceylon Observer*, and also of Mr. Archer, a correspondent of the same paper, to be sufficiently obvious as to have become a subject of popular observation; and Dr. W. W. Hunter has contributed some facts, on the authority of Mr. Robinson, which shew that, in Southern India, there is a marked tendency to the recurrence of periods of scarcity about the time of minimum sun-spots.

It may be expected that any cyclical variation of the kind will be more distinctly manifested in the weather and productiveness of lands in the tropical zone, where the action of the sun is most direct, and the seasonal changes most regular, than in extra-tropical regions, where the non-periodic vicissitudes of the climate are very great, and depend largely on the conditions that prevail in more or less remote parts of the globe. And such appears to be the case. It is only in Ceylon that, as far as we know, the cyclical variation of the rainfall and of cereal produce has become a matter of popular observation, and such places as Madras and the Mauritius shew the cyclical variations of the rainfall far more distinctly than most other places. In Northern India the coincidence is far from distinct, and in the rainfall registers of Calcutta is not recognisable. Even in Madras it is only by taking the average of many sun-spot cycles that the coincidence of the rainfall variation is rendered distinct because, by this proceeding, the more obvious and striking irregularities are to some extent eliminated. If the amounts of rainfall recorded in each year at Madras be plotted as the ordinates of a curve, a simple inspection of the diagram would scarcely suggest that the rainfall varies in an eleven years' cycle. Thus the rainfall of 1860, a year of maximum sun-spots, was lower than that of any other year between 1832 and 1867, and in many other cases the curve makes a dip (indicating a decreased rainfall) just about the the sun-spot maximum. It is not certain how far the periodicity of the time of famines in Southern India is a valid conclusion since Dr. Hunter has adduced such evidence only as tells in favour of a cyclical variation, while he admits that a selection has been made from the whole evidence available. But if we take Northern India into consideration, we find that the worst famine during the present century, that of 1837-38, was produced by the deficient rainfall

of two consecutive years of maximum sun-spots, and the famine of 1861 in the North-Western Provinces followed on the maximum sun-spot year 1860. It is very much to be desired that some person accustomed to rigorous scientific inquiry should collect and discuss the record of Indian famines, in some such manner as Mr. Meldrum has discussed the records of cyclones, *viz.*, by instituting a numerical comparison of the statistics of their extent and intensity. Till this has been done, we shall scarcely be justified in any more definite statement than that, *primâ facie*, the recurrence of years of dearth in Southern India seems to confirm the justice of Sir W. Herschell's hypothesis.

In the following table I have brought together such data as I have been able to collect for illustrating the variation of the rainfall at six stations in India, *viz.*, Madras, Bangalore, Bombay, Nagpur, Jubbulpore and Calcutta. The last column gives Wolf's relative numbers of sun-spot frequency.

I.

Registered rainfall at six stations in India, and Wolf's relative sun-spot numbers.

Year.	Annual rainfall in inches.						Wolf's relative number of sun-spots.
	Madras.	Bangalore.	Bombay.	Nagpur.	Jubbulpore.	Calcutta.	
1813 ...	45·11	...	...	...	...	...	18·7
1814 ...	32·41	...	...	...	...	...	20·0
1815 ...	56·00	...	...	...	...	...	35·0
1816 ...	41·16	...	...	...	...	...	45·5
1817 ...	63·56	...	103·60	...	...	...	43·5
1818 ...	76·25	...	81·07	...	...	...	34·1
1819 ...	36·33	...	77·90	...	...	...	22·5
1820 ...	70·01	...	77·34	...	...	...	8·9
1821 ...	47·13	...	82 59	...	...	...	4·3
1822 ...	59·61	...	112·22	...	...	...	2·9
1823 ...	26·62	...	61·70	...	..	...	1·3
1824 ...	33·72	...	33·87	...	...	...	6·7
1825 ...	56·05	...	72·24	...	...	...	17 4
1826 ...	60·73	...	78·49	57·61	...	...	29·4
1827 ...	88·41	...	81·03	53·01	...	...	39 9
1828 ...	37·89	...	121·98	46·49	...	...	52·5
1829 ...	36·87	...	65·65	50·25	...	59·94	53·5
1830 ...	32·48	...	71·86	32·80	...	63·28	59·1
1831 ...	44·35	...	101·53	65·31	...	56·90	38·8
1832 ...	18·45	...	74·09	36·71	...	50·72	22·5
1833 ...	37·11	...	71·39	...	...	60·56	7·5
1834 ...	39·00	...	70·47	...	...	68 73	11·4
1835 ...	41·47	...	62·61	...	...	85·50	45·5
1836 ...	44·76	...	87 51	...	...	45·66	96·7
1837 ...	49·26	44·30	64·58	...	...	43·61	111·0
1838 ...	52·38	16·00	50·78	...	...	52·99	82·6
1839 ...	53·07	32·40	73·62	...	...	64·97	68·5

Registered rainfall at [illegible] *stations in India, and Wolf's relative sun-spot numbers.*—concluded.

Year.	Annual rainfall in inches.						Wolf's relative number of sun-spots.
	Madras.	Bangalore.	Bombay.	Nagpur.	Jubbulpore.	Calcutta.	
1840 ...	58·65	30·20	63·15	...	...	59·41	51·8
1841 ...	58·32	38·00	71·49	...	...	60·25	29·7
1842 ...	36·48	31·20	95·16	...	...	76 12	19 5
1843 ...	50·28	37·20	59·27	...	...	64·34	8·6
1844 ...	65·36	34·40	65·40	...	...	73·86	13·0
1845 ...	37·65	32·70	54·73	...	44·92	60·92	33·0
1846 ...	79·81	40·00	87·48	...	58·55	76·44	47·0
1847 ...	80·99	37·50	76 01	...	44·96	72·36	79·4
1848 ...	54·76	40·30	75·86	...	35·12	58·69	100·4
1849 ...	39 81	27·80	114·89	...	46·92	70·51	95·6
1850 ...	36·88	49·40	50·24	...	44·59	76·28	64·5
1851 ...	64·32	35·30	96·07	...	38·54	64·16	61·9
1852 ...	72·69	55·10	69·27	...	76·05	81·41	52·2
1853 ...	35·82	34·70	62·55	...	59·80	52·08	37·7
1854 ...	43·20	29·90	82·14	...	52·79	66·47	19·2
1855 ...	32·32	27·10	41·18	26·10	57·97	70·36	6·9
1856 ...	46·99	48·30	65·92	46·36	43·96	64·23	4·2
1857 ...	52·95	30·40	51·27	36·23	51·08	68·97	21·6
1858 ...	48·50	37·80	62·45	35·19	39·02	59·76	50·9
1859 ...	55·14	26·60	77·61	34·40	49·01	68·66	96·4
1860 ...	27·64	33·20	62·15	45·11	48·35	52·61	98·6
1861 ...	37·19	30·51	76·91	45·89	45·03	89·19	77·1
1862 ...	38·18	37·30	73·63	35·82	39·10	73·48	59·4
1863 ...	54·61	35·80	77·68	39·69	59·45	61·15	45·7
1864 ...	47·23	33·60	45·57	34·66	45·43	84·22	47·1
1865 ...	41·64	36·00	77·85	44·56	60·42	61·58	32·5
1866 ...	51·39	33·80	78·44	43·11	53·11	65·74	17·5
1867 ...	24·37	63·99	62·30	57·75	73·10	72·73	7·3
1868 ...	41·43	32·46	62·12	25·49	28·80	91·49	37·3
1869 ...	32·31	40·41	91·66	33·38	62·77	62·00	73·9
1870 ...	74·10	29·04	66·21	41·63	77·78	60·26	139·1
1871 ...	56·35	29·10	40·58	46·75	59·22	93·31	111·2
1872 ...	73·67	40·75	76·48	40·94	67·19	51·05	101·7
1873 ...	51·83	29·13	69·70	30·63	46·11	45·27	66·3
1874 ...	62·90	56·54	82·18	40·88	86·93	61·48	44·6
1875 ...	37·12	22·06	84·56	54·86	51·63	59·89	...
1876 ...	21·72	17·34	50·01	37·42	56·63	80·23	...

Having subdivided the rainfall returns of each station into series of eleven years, and taken the average of the rainfall in each of the homonymous years of the series, in the manner adopted by Mr. Meldrum, and which has also been followed by Dr. Hunter, the result is shewn in the following tables, A, B, and C. The first of these gives, for each station, the mean of each year of the eleven-year series; the second the differences of these means above or below the rainfall of the whole period recorded, and the third the same differences estimated as a percentage of that average. The first table also shews the number of years from which each average has been obtained.

A.

Average rainfall according to the 11-year cycle at six stations.

Year.	Madras.		Bangalore.		Bombay.		Nagpur.		Jubbulpore.		Calcutta.	
	Years.		Years.		Years.		Years.		Years.		Years.	
1860 &c. ...	6	50·95	4	26·52	5	69·89	3	48·29	3	51·50	4	67·35
1861 " ...	6	50·38	4	38·27	6	83·81	3	44·44	3	52·27	4	70·37
1862 " ...	6	54·35	4	32·98	6	74·88	3	38·90	3	41·25	5	60·45
1863 " ...	6	52·88	4	46·36	6	75·06	3	37·79	3	74·14	5	65·51
1864 " ...	6	45·17	4	30·39	6	77·78	3	51·61	3	52·29	5	65·84
1865 " ...	6	37·07	4	30·11	6	70·99	3	39·56	3	56·61	5	64·67
1866 " ...	5	49·16	3	31·77	5	73·73	2	34·60	2	55·54	4	67·63
1867 " ...	5	34·93	3	48·33	5	63·02	2	52·06	3	53·99	4	66·65
1868 " ...	6	49·08	3	34·29	5	59·47	2	30·86	3	46·14	4	80·60
1869 " ...	6	49·17	3	38·57	5	77·97	2	34·29	3	48·92	4	59·95
1870 " ...	6	58·33	4	35·06	5	72·55	3	44·55	3	53·97	4	57·81
Mean ...	64	48·51	40	35·44	60	72·97	29	42·04	32	53·26	48	65·91

B.

Difference of each average year of cycle from the local mean.

Year.	Madras.	Bangalore.	Bombay.	Nagpur.	Jubbulpore.	Calcutta.
1860 &c. ...	+ 2·44	− 8·92	− 3·08	+ 6·25	− 1·76	+ 1·44
1861 " ...	+ 1·87	+ 2·83	+ 10·84	+ 2·40	− 0·99	+ 4·46
1862 " ...	+ 5·84	− 2·46	+ 1·91	− 3·14	− 12·01	− 5·46
1863 " ...	+ 4·37	+ 10·92	+ 2·09	− 4·25	+ 20·88	− 0·40
1864 " ...	− 3·34	− 5·05	+ 4·81	+ 9·57	− 0·97	− 0·07
1865 " ...	− 11·44	− 5·33	− 1·96	− 2·48	+ 3·35	− 1·24
1866 " ...	+ 0·65	− 3·67	+ 0·76	− 7·44	+ 2·28	+ 1·72
1867 " ...	− 13·58	+ 12·89	− 9·95	+ 10·02	+ 0·73	+ 0·74
1868 " ...	+ 0·57	− 1·15	− 13·50	− 11·18	− 7·12	+ 14·69
1869 " ...	+ 0·66	+ 3·13	+ 5·00	− 7·75	− 4·34	− 5·96
1870 " ...	+ 9·82	− 0·38	− 0·42	+ 2·51	+ 0·71	− 8·10

C.

Difference of each average year of cycle as percentage of the local mean.

Year.	Madras.	Bangalore.	Bombay.	Nagpur.	Jubbulpore.	Calcutta.
1860 &c. ...	+ 5·0	− 25·2	− 4·2	+ 14·9	− 3·3	+ 2·2
1861 " ...	+ 3·9	+ 8·0	+ 14·9	+ 5·7	− 1·9	+ 6·8
1862 " ...	+ 12·0	− 6·9	+ 2·6	− 7·5	− 22·5	− 8·3
1863 " ...	+ 9·0	+ 30·8	+ 2·9	− 10·1	+ 39·2	− 0·6
1864 " ...	− 6·9	− 14·2	+ 6·6	+ 22·8	− 1·8	− 0·1
1865 " ...	− 23·6	− 15·0	− 2·7	− 5·9	+ 6·3	− 1·9
1866 " ...	+ 1·3	− 10·4	+ 1·0	− 17·7	+ 4·3	+ 2·6
1867 " ...	− 28·0	+ 36·4	− 13·6	+ 23·8	+ 1·4	+ 1·1
1868 " ...	+ 1·2	− 3·2	− 18·5	− 26·6	− 13·4	+ 22·3
1869 " ...	+ 1·4	+ 8·8	+ 6·9	− 18·4	− 8·1	− 9·0
1870 " ...	+ 20·2	− 1·1	− 0·6	+ 6·0	+ 1·3	− 12·3

The figures in Table C are all comparable with each other, the weight or relative value of each being directly as the number of years which have

yielded the average. If, then, we multiply the groups of figures in each horizontal line of this table by the numbers of years respectively corresponding to them in Table A, add the products, and divide the sum by that of the multipliers, we obtain the general average excess and deficit of each of the homonymous years in the form of a percentage of the mean rainfall as follows :—

1860 &c.	....	− 1·9	per cent. of average
1861 „	...	+ 7·0	„ „
1862 „	...	− 2·6	„ „
1863 „	...	+10·0	„ „
1864 „	...	+ 0·1	„ „
1865 „	...	− 8·4	„ „
1866 „	...	− 1·6	„ „
1867 „	...	− 1·9	„ „
1868 „	...	− 4·0	„ „
1869 „	...	− 1·2	„ „
1870 „	...	+ 3·5	„ „

In this last table the cyclical variation of the rainfall is very distinctly indicated, but the increase and decrease are by no means regular. If, however, for the purpose of clearing the greater irregularities, we substitute for the above means, the figures obtained by adding to each year's average half those of the preceding and the succeeding years, and dividing the sum by two, we obtain the following :—

1860 &c.	...	...	+1·7	per cent. of average.
1861 „	...	...	+2·4	„ „
1862 „	...	...	+3·0	„ „
1863 „	...	...	+4·5	„ „
1864 „	...	...	+0·5	„ „
1865 „	...	...	−4·6	„ „
1866 „	...	...	−3·4	„ „
1867 „	...	...	−2·3	„ „
1868 „	...	...	−2·8	„ „
1869 „	...	...	−0·7	„ „
1870 „	...	...	+1·0	„ „

Now, the 1866 group is that which corresponds to the average sun-spot minimum, and the 1870 group to the sun-spot maximum. Hence it appears that the average minimum of rainfall somewhat anticipates the former, while the maximum rainfall tends to occur three or four years after the latter; but so great are the fluctuations of the rainfall at any given station, that every additional station brought into the average considerably modifies the result, and we are not justified in drawing any conclusion more definite than this,—that, in tropical India, the rainfall tends to fall somewhat below the average about the time of minimum sun-spots, and to rise above it about or somewhat after that of

maximum sun-spots. The variation is much greater and more distinct at Madras than any other station yet examined. If we reduce the irregularities of the figures in the Madras column of Table B, by the process followed for the column of general mean percentages, we obtain the following series:—

1860 &c.	...	...	...	+ 8·5	per cent.
1861 „	...	...	...	+ 6·2	„
1862 „	...	...	...	+ 9·2	„
1863 „	...	...	...	+ 5·8	„
1864 „	...	...	...	− 7·1	„
1865 „	...	...	...	−13·2	„
1866 „	...	...	...	−12·7	„
1867 „	...	...	...	−14·0	„
1868 „	...	...	...	− 6·0	„
1869 „	...	...	...	+ 6·0	„
1870 „	...	...	...	+11·7	„

which shews an average extreme difference of 25 per cent. between the maximum and minimum.

We must not, however, hastily conclude that other stations in Southern India show a variation as great and distinct as that of Madras. At Bangalore, for instance, the variation is scarcely traceable in the series of years for which we have a record of the rainfall.[1] It is very probable that places on the coast line are more favourably situated for affording evidence of a cyclical variation of rainfall than those in the interior of the country, where great variations in the quantity of the rain are more dependent on variations in the local distribution of pressure. That the cyclical variation of rainfall depends on the amount of evaporation, which is least when the solar disc is most free from spots, and when its radiation is least intense, and *vice versâ*, seems to be indicated by the following table of the mean annual vapour tension of Colombo since 1870. The figures are deduced from observations of the psychrometer made at 10 A.M. and 4 P.M., under the superintendence of Colonel A. B. Fyers, R.E.

Annual mean vapour tension at Colombo.

Year.		V. T.	Year.		V. T.
1870	...	·886 inch.	1874	...	·869 inch.
1871	...	·896 „	1875	...	·843 „
1872	...	·878 „	1876	...	·826 „
1873	...	·875 „			

The table shews a tolerably regular decrease since 1871, the year following that of maximum sun-spots.

[1] At Mysore, however, the registers of which for 40 years I have obtained since the above was written, the cyclical variation is more distinct, though small.

STORMS.

125. Classification of storms.—Any violent wind may be termed a *storm*, whether it be accompanied or not by electric discharges, rain, hail, &c.: for the definition of the term, like that of most others current in ordinary language, is not very rigorously restricted. In point of fact, no very precise line can be drawn between those vortical movements of the atmosphere, which have been described in the preceding section, and which are accompanied by a copious discharge of rain, without any very vialent wind, and the fiercest and most destructive cyclones; and again, though most storms are more or less cyclonic in character, the stormy wind which precedes an ordinary nor'-wester, and is occasionally of destructive violence, is not a cyclonic wind, but, on the contrary, blows outwards from beneath the margin of the advancing cloud bank. A precipitation of rain, hail, &c., is generally an important part of storm phenomena; but the dust-storms of Upper India are frequently unaccompanied by rain, although in many cases they are certainly vortical and cyclonic, and the electrical discharges which accompany them are frequently very copious.

Every storm is the result of a great disturbance of atmospheric equilibrium, and probably, in all cases, an ascending convection current is an essential part of the phenomenon. But this may be brought about, either rapidly by direct heating, as is the case with the dust-storms above referred to, and in part the nor'-westers of the Lower Provinces; or it may be the result of continued and progressive condensation, as seems to be the case in those fierce cyclones which are generated over Indian seas, especially the Bay of Bengal, and chiefly at the change of the monsoons.

These latter may be treated as a separate class, in virtue of their being generated over the sea, as well as on account of their fierceness and destructive power, and the dread accompaniment of the storm-wave, which is peculiar to them, and which is the great agent of destruction, when the storm reaches a low shore with a shelving fore-shore beyond. And in the present state of our knowledge, this classification of land-storms and sea-storms, if not strictly scientific, is as convenient as any other that we can adopt.

126. Land-storms.—The immediate cause of those storms which are generated over the land is probably, in most cases, the high temperature imparted to that stratum of the atmosphere that rests immediately

on the ground, by the diurnal heating of the sun; and also by the increased production of vapour, which, mingling with the same stratum, to some small extent reduces its density relatively to the superincumbent strata, and at the same time furnishes a store of energy (§ 34) which becomes active when, after a lapse of time, the vapour has risen to a height where it is condensed as cumulus cloud. If the atmosphere is exceedingly dry, as is the case in April, May, and in the earlier part of June in the Punjab and the upper part of the North-Western Provinces, the vertical equilibrium of the atmosphere is destroyed, when this heating of the lowest stratum becomes such, that the vertical decrease of temperature exceeds 1° in 183 feet (§ 31): in a more humid atmosphere, such as prevails at the same time of the year in Bengal, and even occasionally in the Upper Provinces, it is probably in the lower cloud stratum that the original disturbance of equilibrium is set up; and we have seen (§ 33) that this may take place when the vertical decrement of temperature is only 1° in 400 feet or less, according to the temperature and pressure of the stratum. The former conditions are probably those which give rise to the dust-storms so common in the Punjab, the latter to the nor'-westers of the Lower Provinces.

127. Dust-storms of Upper India and Sind.—Since Dr. Baddeley published a description of these storms in the Philosophical Magazine for 1850[1] and Journal of the Asiatic Society of Bengal for 1852, no one, as far as I am aware, has given any especial attention to this subject; which is, nevertheless, one of peculiar interest, since it is at least probable that these dust-storms are the most considerable instances of convection currents set up in dry air which are anywhere to be met with. They are accompanied by a very high electric tension, but it is evident that the electric phenomena have been misunderstood by Dr. Baddeley, who speaks of the storm being "caused by spiral columns of the electric fluid passing from the atmosphere to the earth." His observations, however, apart from his theoretical views, are very valuable, and the following descriptive passages are extracted from his writings:—

"The violent dust-storms are by some supposed to commence at the foot of the hills. I cannot tell whether this be the case or not, but should think that they do not necessarily do so, as many often originate in extensive arid plains; and the rarification of the air, from great and long continued heat, may be in some way connected with the exciting cause. Some of them come on with great rapidity, as if at the rate

[1] Reprinted in volume XIX of the Journal of the Asiatic Society of Bengal.

of from 40 to 80 miles an hour. They occur at all hours, oftentimes near sunset.

"The sky is clear, and not a breath moving; presently a low bank of clouds is seen in the horizon, which you are surprised you did not observe before. A few seconds have passed, and the cloud has half filled the hemisphere; and now there is no time to lose—it is a dust-storm, and, helter-skelter, every one rushes into the house in order to escape being caught in it." A conducting rod or wire having been erected on a house, and the end brought into a room and connected with an electrometer, "the electric fluid continues to stream down the conducting wire unremittingly during the continuance of the storm, the sparks often an inch in length and emitting a crackling sound, the intensity varying with the force of the storm and more intense during the gusts." Dr. Baddeley points out the apparent identity of character between these great dust-storms and the small dust-whirls which are common in all parts of India in dry, hot weather, and are of all degrees of magnitude, from a few feet only in height, up to some thousands of feet. On the approach of one of the larger storms, "a broad wall of dust is observed rapidly advancing, apparently composed of a number of large vertical columns of dust rolling onwards, each preserving its respective position in the moving mass, and each column having a whirling motion of its own * * *. During a storm, when the whole atmosphere is filled with dust, * * * no such marked indication of their presence is perceptible. On such occasions, however, the peculiar motions of a vane, oscillating as it constantly does from 3 to 4 points or more during the passing gusts, makes plainly enough the action of these spirals." This, as Dr. Baddeley correctly points out, is also the behaviour of the vane in a cyclone, and probably in all stormy winds that blow in gusts. In some cases the storm is not followed by rain, but in others "a fall of rain suddenly takes place, and instantly the stream of electricity ceases or is much diminished, and when it continues, it seems only on occasions, and when the storm is severe and continues for some time after. The barometer rises steadily throughout."[1] As I have said above, the most probable explanation of these storms is, that they arise from the excessive heating of the lowest stratum of the atmosphere, and its consequent expansion to such an extent, that the vertical equilibrium is destroyed, and convection currents are consequently set up suddenly. That they should be accompanied with great electric tension is only what might be expected

[1] Dust-storms often end with a few drops of rain, but not always; but they are always followed by a considerable reduction of temperature.

in a comparatively insulating atmosphere loaded with solid particles in violent movement, by the friction of which, therefore, electricity must be copiously generated. It is possible, however, that electric convection may play a part in the phenomenon, perhaps only as a secondary cause. The existing observations are quite insufficient to do more than suggest explanations.

128. The Simoom.—By most writers on meteorology this wind of the desert is treated of as merely a particular case of a hot wind; and it is considered that its fatal effects are traceable to its intense heat and dryness. But there seems some reason for doubting whether there has not been some misconception on this matter. Hot winds are generally loaded with fine dust, but Palgrave describes the simoom experienced by him in the Arabian desert as perfectly free from dust; and some facts collected by Dr. H. Cook, on cases of the simoom in Upper Sind and Cutchee, certainly seem to sanction the inference, that something more than mere heat and dryness have acquired for this scourge of the desert its ominous name of the 'Poison-wind'. The following passages are quoted from a report by Dr. H. Cook of Bombay, at one time in medical charge of the Khelat Agency:—

"At the close of the hot weather in 1856, a party of five men were crossing the Put of Shikarpur, being on their way from Kandahar to that city; the blast unfortunately crossed their path, killed, if I recollect rightly, three of them, and disabled the remaining two.

"In the year 1851, during one of the hot months, certain Officers of the Sind Horse were sleeping by night on the top of General Jacob's house at Jacobabad. They were awakened by a sense of suffocation, and an exceedingly hot oppressive feeling in the air; while, at the same time, a very powerful smell of sulphur was remarked to pervade the atmosphere. On the following morning a number of trees in the garden were found to be withered in a very remarkable manner. It was described as if a current of fire, above 12 yards in breadth, had passed through the garden in a perfectly straight line, singeing and destroying every green thing in its course, entering on one side, and passing out on the other; its track was as defined as the course of a river.

"The Moonshee of Major Henry Green, Honorary Aid-de-Camp to the Governor-General, and Political Agent at Khelat, is a native of Bhag in Cutchee, and gave the following description of the effects of one of these blasts of which he was both the eye-witness and sufferer. He was travelling in company with two others, near Chilgherry, the site of a buried city in Cutchee, about seven miles south-east of Bhag:

they were all mounted. About 2 A.M. the blast struck them. He was sensible of a scorching sensation in the air, like the blast of an oven, but remembers nothing further, as all three were immediately struck to the earth. They were carried to Bhag, where every attention was afforded them, and they ultimately, after some days of sickness, recovered. He states that such phenomena are frequent in the desert; that the hot blast is generally preceded by a cold current of air; that it destroys every green thing in its course, and is most frequently fatal to human life. That the bodies of the dead quickly decompose, their flesh is withered, its firmness and consistency destroyed, so that it falls or may be plucked from the bones, and this not after decomposition has commenced, but immediately on death taking place."

"During the past hot season, many (upwards of 15) lives have been lost in the desert to the north-west of Jacobabad. Many of these may undoubtedly be attributed to sun-stroke, but that the following is a well-marked case of the effects of the simoom admits of little doubt:—

"Two syces with two camels were sent to Minooti (20 miles to the north-west of Jacobabad) for grass; not returning at the proper time, it was feared that some accident had happened, and search was made. All four bodies were found lying together in one spot perfectly dead. Their death had been evidently instantaneous."

Dr. Cook, in commenting on these cases, sums up the following characteristics of the simoom:—

1. It is sudden in its attack.
2. It is sometimes preceded by a cold current of air.
3. It occurs in the hot months (usually June and July).
4. It takes place by night as well as by day.
5. Its course is straight and defined.
6. Its passage leaves a narrow knife-like track.
7. It burns up and destroys the vitality of animal and vegetable existence in its path.
8. It is attended by a well-marked sulphurous colour.
9. It is described as being like the blast of a furnance, and the current of air in which it passes is evidently very greatly heated.
10. It is not accompanied by dust, thunder or lightning; and he suggests that its fatal effects are due to its being charged with ozone.

Unfortunately, the evidence is at present too meagre to admit of any decided opinion, but the subject is well worthy the attention of those

whose residence in Cutchee and Upper Sind afford them opportunities of collecting *and sifting* further facts.

129. **North-Westers.**—The dust-storms already described differ in some important respects from the nor'-westers of the Lower Provinces, and, indeed, other parts of India, which are akin to the summer storms common in Europe, but generally more violent. These latter occur chiefly in the months of March, April and May, when the sea wind which carries vapour some hundreds of miles into the interior is met by the dry westerly winds described in § 93, and it is in the region of ascending currents between these two winds, that nor'-westers originate. The name is taken from the fact that, if they move, they always advance seaward, that is driven by the land wind, which blows (from the west or north-west in Northern India) above the stratum of the cumulus clouds, even though the sea wind may be blowing below, almost up to the time that the storm bursts.

From Calcutta, throughout the months above mentioned, a low bank of clouds is almost always visible to the west and north-west in the afternoon; and on the approach of a nor'-wester this rises higher and higher; a sheet of pallio-cirrus, frequently with a hard, straight edge, advancing before the lower mass of the pallio-cumulus. At other times, a sheet of cirro-stratus forms over the greater part of the sky early in the afternoon, becomes thicker as the day advances, and at last a heavy mass of pallio-cumulus forms beneath it and completes the storm-cloud. The approach of a nor'-wester is heralded by a sudden rise of the barometer, and by a strong stormy wind blowing outwards from beneath the storm cloud, and always either seaward or at least from some point between east and round by north to south-west. I do not remember to have ever observed a storm advance from the direction of the sea. The wind that precedes the rain is very cool; I have seen the thermometer sink 20° in the space of ten minutes on its approach. It raises clouds of dust and blows in gusts, sometimes with great force. Pressures of 50 lbs to the square foot have been sometimes registered by it on the Osler's pressure gauge at the Surveyor-General's Office; and on one occasion, the first and fiercest of these storms that I have ever witnessed, *viz.*, on the 14th May 1856, the Calcutta race-stand was blown down, and for upwards of a quarter of an hour the wind had the force of a severe gale; during the whole time the air was so thick with dust, that objects could not be distinguished even at a few yards distance. On this occasion a large quantity of hail fell.

The storm-cloud is probably in all cases the seat of an ascending convection current; and occasionally, the course of the inflowing

currents is rendered visible by small tufts of cloud, which form in the transparent atmosphere beyond the edges of the storm-cloud, and drift up into it, when their horizontal motion ceases and they become absorbed. The pallio-cumulus is always in a state of great internal disturbance; and, after the first onset, it either does not advance further, or its advance is very slow. Frequently, in one of these storms, the wind and the movement of the clouds change, during the storm, through many points of the compass. At other times, the wind almost ceases when the rain falls. On one occasion in Calcutta, a nor'-wester which occurred about 9 in the evening was followed by a hot wind from the west, which sent up the thermometer several degrees.

130. Hail-storms.—Hail sometimes falls in a nor'-wester, more especially between February and May. It occurs in all parts of India, and even in Ceylon. The stones are generally of a large size, as much as ½ or ¾ inch in diameter, and sometimes much larger; and the small soft hail, the "graupel" of the Germans, which is so common in England, is unknown in India. The best collection of data on hail-storms in India is that published by Dr. Buist in the British Association Report for 1855, from which I take the following particulars.

The relative frequency of hail-storms at different seasons of the year is shewn in the following table :—

Distribution of recorded hail-storms in India according to months.

January	5	July	2
February	20	August	0
March	31	September	2
April	34	October	3
May	17	November	4
June	4	December	5

Thus, as Dr. Buist remarks, hail falls chiefly in the driest months, February, March and April (see § 109), and more especially in April. The cases of hail in June and July were in Central India, when the rains were late in setting in; and it is noticed that, in these cases, the hail-stones were always small and the falls light, in comparison with those at other seasons of the year.

With respect at the hours at which hail-storms occur, it appears from the notes of Dr. Spilsbury, that of 30 storms recorded by him, 10 are set down as occurring at 3 or 4 P.M., 1 at 4 P.M., 4 at sunset, 5 at 11 A.M., or noon, 2 at 2 P.M., 1 at 8 A.M., and 1 at 9 A.M. Only 3 occurred after dark, and none later than midnight.[1]

[1] One occurred at Calcutta on the 16th March of this year 1877, which began 5 minutes before midnight and lasted a quarter of an hour. The stones were unusually large, five of them yielding three fluid ounces of water.

In respect of locality, Dr. Buist observes "that whereas, the delta of the Ganges down to the sea, in latitude 22°, and but little raised above the highest tide, whose damp, tepid atmosphere contrasts as strikingly as possible with the pure, crisp, vapourless air of the mountains, is the favourite locality of hail-storms; and whereas these are frequent along the western shore of the Bay of Bengal,—from Surat south to Ceylon, in corresponding latitudes and altitudes on the Malabar coast, hail is a thing nearly unknown; though appearing in abundance immediately to the north-westward, along the shores of Cutch and Sind, and to the eastward, as at Satara, Mahableshwar in the Ghâts, and all over the Deccan, as soon as we get some 1,500 feet above the level of the sea."

The general conclusion that may be drawn from these data is, that hail-storms are generated at the meeting of a very dry wind with a damp wind. The Gangetic delta in the months of February, March and April, is by no means a characteristically humid tract, comparable with the Malabar coast of India; but is the place of meeting between the dry land winds of the interior and the more humid winds from the sea; and, at a certain moderate altitude, the land wind blows outwards to the south-east during the whole of the afternoon; while the sea wind may prevail for one or two thousand feet above the land surface.

One of the most remarkable hail-storms, both on account of the locality, and the (authenticated) great size of the hail-stones, is that which occurred at the hill station of Naini Tal on the 11th May 1855. Of the stones weighed by the writer of the description, "some weighed 6, others 8, others 10 ounces, and one or two more than 1½ lbs. avoirdupois, with circumferences varying from 9 to 13 inches." Certain instances of larger masses than these are recorded more or less vaguely; but it is difficult to distinguish between masses of ice that have actually fallen as such, and the agglomerated stones which may have been found frozen together by regelation after their fall. Dr. Buist classifies hail-stones as follows, according to their structure: "1,—pure crystalline masses, either globular or lenticular, internally transparent, but covered externally with a coating of opaque white ice; 2,—the same, but with a star of many points in the centre, the principal rays of which extend to the circumference, the section being singularly beautiful; 3,—nearly globular, consisting of thin, concentric layers, like the coatings of an onion, of different degrees of transparency; as if increased in size, by film after film being frozen over them in their descent; and, 4,—agglutinated masses of hail-stones, connected together subsequently to their primary forma-

tion; if indeed these last, which may consist in part of any of the previous three varieties, are entitled to the name of hail-stones at all." Some specimens of the third class of hail-stones, as above defined, but having an irregular external envelope of clear ice, which fell at Calcutta on the 24th March 1865, were figured by the author in the 33rd volume of the Journal of the Asiatic Society of Bengal.

Hail-storms are always preceded by a peculiar noise, which probably arises from the hurtling of the hail-stones in the air; and has been compared by one writer to "that produced by a number of railway trains rushing by at no great distance," and by the describer of the Naini Tal storm above quoted, to "innumerable bags of walnuts pouring out their contents in the heavens." In general, the fall of hail is accompanied by vivid lightning discharges and very violent gusts of wind, but these are not invariable phenomena.

The concentric structure of the stones, and the fact that the coats frequently consist of alternations of opaque and transparent ice, may perhaps be explained by assuming that, during the fall of the nucleus, it passes through strata alternately above and below the freezing point, and receives additions of snow crystals and water alternately, the latter freezing when the stone passes into another stratum below the freezing point. Many points connected with formation of hail are still involved in great obscurity.

131. Whirlwinds, Water-spouts, &c., Tornados.—Tornados are circular storms of small dimensions, but of great violence; they are sometimes as much as a mile in diameter, but generally much less; and are very destructive wherever they pass. Those of which I have any record appear to have been short-lived, and to have restricted their ravages within very moderate limits. They occur generally in the earlier months of the year; and not unfrequently originate as water-spouts over rivers. One, which is described by Mr. Fasson in the Proceedings of the Asiatic Society of Bengal for 1875, originated over the Jamuna river (the local name of the present main stream of the Brahmaputra), which, at the place in question, is three miles wide. "The day (26th March 1875) had been hot, without a breath of wind. Clouds lay in the south-west quarter only. About an hour after sunset, the eddy, already a roaring whirlwind, carrying with it a swirling water-spout some 10 feet in height, judging from the height of the water-mark on the bank, struck the eastern bank of the river at Shakhairlia Khâl. Here were moored eighteen large boats, most of them freight-carrying masted boats of many maunds burden. All

these were instantly overturned, shattered, stove in, or flung on shore. One large boat was lifted bodily into the air, carried over the bank 15 feet in height, and dashed to pieces in a field some 30 yards inland. * * * Another khál, some 300 yards to the north, remained tranquil and undisturbed. The whirlwind passed on north-eastward, over some half mile of maidan, covered with *cheena* crops. Here no trace of its progress appears; the crops are unhurt and not even flattened, but shew no sign. Then came the village of Uladah, stretching north and south, some half a mile. In a moment the hurricane had passed through, leaving a strip, 250 yards broad, of utter devastation, while all remained untouched to the north and south of its path. In this strip, not a house was left standing; the roofs were whirled off, the walls stripped away, the wooden posts torn away with such violence as to break up and disintegrate the wooden *bhitas* in which they had been fixed. All the plantain trees were wrenched off and uprooted; twelve large mango trees were torn up by the roots; all the trees that remained standing were stripped of their branches, large and small, which were snapped off close to the trunk. * * * The bamboo clumps were twisted round and laid flat, the stems being broken off near the roots. * * * A dead cow was found among the broken branches of a mango tree, some thirty feet from the ground. The whirlwind continued its north-east course across a maidan of more than a mile, covered with *cheena* for the most part. Here again it left no trace, except where a long strip of bushes ran along an *il*, parallel with the direction of the storm. These were flattened. Then the storm struck the northern end of the village of Chanbárí. * *" The whole course of this whirlwind was about two miles, and the breadth of its track, as above stated, 250 yards. The weather was hot and clear up to the moment of the whirlwind; after it had passed, heavy rain immediately followed. One peculiarity is recorded, which, if the testimony of the villagers is to be credited, would seem to indicate a copious electric discharge, similar to that which characterises the dust-storms already described, and also, probably, identical with that presently to be noticed as accompanying cyclones. Mr. Fasson writes: "All the people speak to a fiery appearance or ruddy glare; some who looked from the khál after the storm had passed, say they at first imagined the villages would take fire, as the whirlwind reached them. It must be remembered, too, that it was all but dark at this time." And again: "Alike at the Khál, at Uladah and Chanbári, the story is, 'we suddenly heard a booming, whirling sound, as loud as the firing of a cannon; all became dark, but with a sort of fiery glare in it; there was a sense of suffocation from the tremendous whirling of the air, and in a moment everything was swept off and

whirled away in all directions.'" A whirlwind of greater diameter, but equally short-lived, which occurred in the neighbourhood of Pandooah (on the East Indian Railway, 38 miles from Calcutta) on the 5th May 1865, is described in the Proceedings of the Asiatic Society of Bengal for that year. The whirlwind crossed the railway line at right angles, and blew down nine telegraph posts in one direction and eleven in the other. The distance between the two central posts, which lay in opposite directions, was 200 feet, which therefore may, perhaps, be taken as the maximum width of the central calm. As in the case of the former storm, it occurred in the evening about 6 P.M. and lasted half an hour, having travelled rather more than a mile, and, in its course, destroyed the greater part of two villages, blown the water with a lot of fishes out of a marsh, and killed 20 persons. In this case, it appears from a chart communicated by the describer of the storm, and also from the direction of the fallen telegraph posts, that the rotation of the wind was, as in cyclones, against the clock.

The formation of tornados and water-spouts is very probably identical with that of dust-storms and "devils," *viz.*, a sudden disturbance of the vertical equilibrium of the atmosphere, whereby an upward rush of air is generated, which rapidly becomes spiral. The spiral motion is a condition practically inseparable from any rapidly ascending or descending fluid current, as may be seen on so small a scale as in a trough of water, when a hole is made in the bottom. Any small deviation from the radial direction of the inflowing air currents, preponderating in one direction, is sufficient to cause gyration. In water-spouts, "devils" and all small whirls, the gyration may be either right-handed or left-handed.

Water-spouts often appear to be formed by the descent of a funnel-shaped mass of cloud, with a whirling tail, which gradually lengthens downwards. The descent is, however, very probably, an optical delusion; and may be due to the formation of a spiral ascending convection current, in which condensation takes place lower and lower, (thus rendering it visible) as the current is drawn from successively lower strata. The long bluish tube which characterises the fully formed water-spout may, perhaps, be an effect of atmospheric refraction, since, owing to the rapidity of the whirling air, the central part of the column must be highly attenuated. The varied forms of water-spouts have been well illustrated by Captain Walter Sherwill, in a paper published in 1860, in the 19th volume of the Asiatic Society of Bengal. They are formed in a still atmosphere, and frequently end in heavy

rain, sometimes in hail. One which occurred at Dum-Dum on the 7th October 1859, was measured by Captain Sherwill with a theodolite, and found to be 1,500 feet in height. It lasted about 25 seconds, and, on its reaching the earth, the cumulus cloud from which it proceeded "burst and was seen pouring down to the earth, not as a shower of rain, but as a heavy mass of water," which put half a square mile of country under water, about half a foot deep.

132. Cyclones.—I have already explained (§ 75) that a *cyclone* is a spiral circulation of the winds around a region of low barometric pressure. This circulation is all that the etymology of the name implies; and, at the present time, it is frequently used in this general sense, in contradistinction to Galton's term *anti-cyclone*. But originally, it was designed by Mr. Piddington as a specific name for those violent storms which are peculiar to certain tropical seas; and the gyration of which was established by the labours of Redfield and Reid in the West Indies, and those of Thom and Piddington himself in the case of Indian seas. The works of Reid and Piddington on this subject are, even to the present day, the familiar guide-books of meteorologists and seamen; and will always remain store-houses of valuable observations collected at the cost of great labour, and with a single-minded devotion to a great and beneficent purpose. And indeed, as regards the empirical characters of these storms, those which are of most practical importance to the seamen, excepting perhaps in one respect, but little has been added to the results of these writers and their contemporaries. They have been sometimes misapprehended by persons who seem to be under the impression that the earlier writers generally regarded cyclones as circulating winds without any spiral indraught. That such is not the case with Redfield and Piddington will be evident to any one who takes the trouble to consult their works in the original.[1] But this error has been committed by some of their interpreters; and, as has been pointed out by Mr. Meldrum and by the late Mr. W. G. Willson, the rules laid down by Reid and Piddington did not sufficiently insist on the fact of the spiral indraught, and have sometimes led to disaster. The physical explanation of cyclonic storms was avowedly left by these authors in a very crude and

[1] See, *e. g.*, Sailors' Hornbook, 4th edition, pp. 108, 113. It must, however, be admitted that Mr. Piddington did not regard the incurving of the winds as a constant and essential character, and he even speaks of the possibility of their sometimes blowing in diverging spirals. The views of Mr. Redfield, the true author of the cyclonic theory, seem, however, to have been more just, and in accordance with our present views.

unsatisfactory state; and although many important advances have been made by Espy, Colding, Ferrel, Reye, Hann, Mohn and Guldberg, to which I may add the name of the latest writer, my colleague, Mr. J. Elliott, meteorologists are, as yet, by no means of one accord on some important points of the theory. I believe, however, that our final accord is not very far off, and the explanation which I shall give in these pages is that which seems to be most consonant with the facts collected in recent years, through the study of the cyclonic storms of the Bay of Bengal; a sea which affords peculiar advantages for the purpose. Before entering on the theory of cyclones and the conditions of their genesis, I will briefly notice the more important empirical laws of those storms, with especial reference to our Indian seas.

133. Spiral course of winds in cyclones.—A cyclone differs from a tornado chiefly by its greater size and duration. Both consist of an atmospheric vortex, a whirlpool of air pouring upwards. The winds of the lower atmosphere blow from all quarters, more or less obliquely towards it; and, in the vortex itself, become more tangential, and at the same time more violent; the greatest strength of the storm being near its centre. But, in the centre, there is an absolute calm; or, at the utmost, light variable winds. This calm region, which is circular or nearly so in form, is sometimes as much as 15 or 20 miles in diameter, at other times not half that extent; and, on its opposite borders, the wind directions are from directly opposite quarters.

The degree to which the winds curve inwards towards the centre, or depart from a truly tangential direction, is a point on which further evidence is desirable. Redfield was of opinion that "it is not probable that, on an average of the different sides, it ever comes near to forty-five degrees from the tangent of a circle; and that such average inclination ever exceeds two points of the compass may well be doubted." But Mr. Meldrum has shewn that, at a considerable distance from the centre, the direction is sometimes radial, or nearly so. In the case of the storms of the Bay of Bengal, the following rule given by Mr. Willson is probably a fair generalisation:—"With the face to the wind, the direction of the centre is from ten to eleven points to the right-hand side." It certainly varies, however, in different storms, and even at different times and in different parts of the same storm; and as the result of a comparison of the charts given by different describers, it seems to me that, on land and in the neighbourhood of land,

the direction is considerably more radial or less tangential than on the open sea. I am, however, entirely of the opinion of Mr. Meldrum and Mr. W. G. Willson, that a rigorous adherence to the rules laid down by Reid, Dove and Piddington, which proceed on the assumption that the winds blow in a tangential direction, and which disregard their spiral convergence, is dangerous in practice and may lead to disaster. A comparison of the two adjoining figures, one of which represents the course of the winds in a cyclone, as assumed in the rules laid down by the above authors, the other that which results from Messrs. Meldrum, Willson's, and my own experience, will facilitate a comprehension of the point at issue and its bearings. If figure 17 were a true representation of the course of the winds in a cyclone, a ship, in the position S, with a south-east wind aft, might, by keeping the wind aft, safely run across the path of the advancing storms and escape injury; but if figure 18 be a more accurate representation, then to follow such a course would infallibly lead the vessel into the very heart of the cyclone.

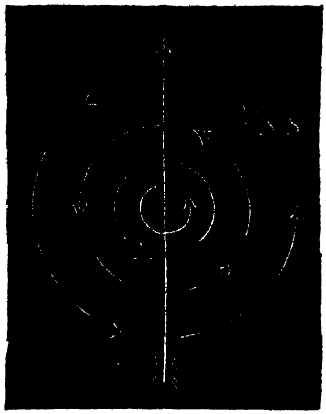

Fig. 17.

Fig. 18.

It has already been explained (§ 75) that the cyclonic circulation of the winds is against the direction of the clock hands in the Northern Hemisphere and with it in the Southern Hemisphere.

134. Barometric Characters.—We have seen that any cyclonic circulation of the winds is around an area of low pressure. And it has long been known that a very great diminution of the pressure, below the average, characterises the cyclone vortex; the central calm being the seat of the minimum pressure. It is not unusual to meet with depressions of one and a half inches in this part of the storm, as compared with those which prevail around, and with the average of the time and place. The lowest well-authenticated pressures, recorded with compared barometers, in Indian storms are, however, seldom lower than 28 inches. In the cyclone of the 30th October 1836, the central calm of which

passed over Madras, the lowest pressure recorded at the Government Observatory was 28·285. In that of the 3rd June 1842, the centre of which passed over Calcutta, and which was recorded as the most severe gale ever felt there, the lowest pressure was 28·278. In that of the 5th October 1864, the centre of which passed over Contai to the south of Calcutta, an aneroid (subsequently compared with the Calcutta standard and corrected to it) shewed a pressure of 28·083, and this is the lowest fairly authenticated reading that I have met with at any *land* station. At Calcutta, which lay 16 miles from the track, the lowest pressure recorded in the same storm was 28·570 inches.

But authentic lower pressures have been recorded at sea. Thus, in the Midnapore and Burdwan cyclone of the 15th October 1874, the barometer on the pilot brig *Coleroon*, when the ship was involved in the central calm, shewed a pressure of only 27·58 inches; and as the instrument was subsequently compared with, and the readings corrected to the Calcutta standard, this may be taken as approximately correct.

The barometric gradient in the vortex of a cyclone is steepest close to the central calm; and consequently, at any place situated on the central track, the fall of the barometer becomes more and more rapid as the centre approaches. In the cyclone of the 5th October 1864, when the pressure at Contai was 28·01, at Calcutta it was 29·34, a difference of 1·36 inches. As the distance between the two places, measured in a direct line, is 70 miles, this represents an average gradient of 1·8 inches in 100 statute miles, or one inch in 48 nautical miles. In the Midnapore and Burdwan cyclone of 1874, at 6 A.M. on the morning of the 16th October, the pressure at Burdwan, during the calm, was 28·48 as observed on an aneroid subsequently corrected to the Calcutta standard. At Calcutta at the same hour it was 29·58. Adding ·086 to the Burdwan reading for the difference of level, this makes a barometric difference of 1·014 between the two places, which are 55 miles apart; and the mean gradient was therefore 1·84 inches in 100 statute miles, and one inch in 47 nautical miles, or nearly the same as in the cyclone of 1864. Another, but somewhat less authentic datum for the same storm at sea, is given by the barometric readings at Saugor Point Light-house and on board the pilot brig *Coleroon*, when the latter was involved in the central calm as above mentioned. But there is, of necessity, some uncertainty about the exact position of the ship. Accepting that given by Mr. Willson, which puts her 50 miles from Saugor Point, there was a barometric difference at 1-15 P.M. of 0·831 inch between the two stations, equal to 1·662 inches on 100 statute miles or 1 inch in 52 nautical miles. At the same hour between Saugor Point and Calcutta (70 miles) there was

a barometric difference of 1·275 miles (allowing for difference of level, and interpolating between the hourly readings actually recorded). This is equal to 1·821 inches in 100 statute miles and 1 inch in 48 nautical miles. These results all accord so nearly, that we may safely conclude that in the vortex of such violent storms as those referred to, the average barometric gradient is rather greater than 1 inch in 50 nautical miles.

As a general rule, the barometer falls gradually for three or four days before the advent of a cyclone, but not invariably. In such cases the pressure falls gradually over the whole of the Bay and the surrounding coasts during the formation of the vortex; and a more rapid fall ensues, when the cyclone has been formed and is advancing towards the place in question. But if the cyclone cradle is distant, and the original area of depression of moderate extent, it may happen that the first intimation of the storm, shewn by the barometer, is that produced by the approaching vortex.

135. Velocity and pressure of winds in a cyclone.—Owing, unfortunately, to the frequent destruction of anemometers, the information available on this head is very scanty. In the Calcutta cyclone of October 5th, 1864, the Osler's anemometer over the Surveyor-General's Office in Calcutta registered a pressure of 36 lbs. to the square foot before it was blown away. But pressures of 50 lbs. have been registered subsequently in an ordinary north-wester, which caused no particular destruction; so that there is no reason to believe, that this pressure nearly represented the extreme force of the storm. In the Midnapore and Burdwan cyclone of 1874, a railway train, exposed to the full force of the wind, was blown over. With the surface of the sides of the several carriages, their height and weight when empty, and the breadth of the rails as data, Mr. W. G. Willson calculated that the least pressure capable of overturning the individual carriages varied from 34 to 55·6 lbs. per square foot, the mean of the whole being 42·8 lbs. to the square foot. In the same storm, a small Robinson's anemometer at Burdwan withstood the cyclone, but was not read for 24 hours. Assuming that, in the interval, it had completed one revolution of the dials, (amounting to 505 miles,) and adding this to the actual record, the total would amount to 672 miles, or an average of 28 miles an hour. But as the wind blew with violence during 8 or 10 hours only, it is probably safe to conclude that at the height of the storm the mean velocity was at least double this amount. In the Madras cyclone of the 2nd May 1872, the Beckley's anemometer over the Madras observatory registered 53 miles in one hour. But mean velocities are a very imperfect criterion of the force of the gusts in such storms, since

the wind continually oscillates from only 5 or 6 lbs. to the square foot up to pressures at least ten times as great. In a small storm on the 1st July 1872, the centre of which passed over Balasore, the highest velocity recorded at Saugor Island, 50 miles from the centre, was 57 miles in one hour.

Ferrel and Colding have given a formula[1], by means of which, the velocity of the wind may be calculated approximately, when the barometric gradient to the storm centre, and the distance of the place from the centre of the wind's gyration are known.

Disregarding friction, the general formula expressing the relation of the barometric gradient to the wind velocity is—

$$\Delta B = 0{\cdot}01011\ ({\cdot}525 \sin \phi + u)\ v \qquad \text{(I)}$$

wherein the barometric gradient ΔB is expressed in inches of barometric difference per 100 nautical miles, ϕ is the latitude, u the angular velocity per hour around the storm centre, and v the velocity of the wind in nautical miles per hour. If r is the distance from the centre of gyration, also in nautical miles, putting $\frac{v}{r}$ for u in this formula when ΔB is known, the value of v is obtained as follows:—

$$v = \sqrt{\frac{\Delta B\ r}{{\cdot}01011} + ({\cdot}262 \sin\phi\ r)^2} - {\cdot}262 \sin\phi\ r \qquad \text{(II)}$$

In the tropics, the terms dependent on $\sin\phi$ are very small, and may be neglected without any error of importance. In a storm, such as those noticed in the preceding paragraph, in which the barometric gradient in latitude 21° 30′ is 1 inch in 50, or 2 inches in 100 nautical miles, the velocity of the wind at a place 50 miles from the centre would be 91 miles an hour, were the centrifugal force of the gyrating wind in equilibrium with the difference of barometric pressures given by observation; and the mean pressure, (not that of the gusts only,) would by Colonel Sir H. James' formula—

$$P = v^2 \times {\cdot}005$$

be not less than 41·4 lbs. to the square foot.

But this assumes that the wind blows in circles, coincident with the course of the isobars; and the charts of several storms which have been plotted from the observations by Mr. W. G. Willson, Mr. J. Elliott and myself, for the Bay of Bengal, shew that such is far from being the case. Taking, for instance, the Midnapore and Burdwan cyclone

[1] American Journal, 1874, third series, volume viii, page 343.
For the development of this important formula, see the note at the end of this work.

as charted by Mr. W. G. Willson, at the moment (4 P.M. of the 15th October 1874,) when the position of the centre was south-west by south) of Saugor Point; and assuming, (which must be very nearly the case,) that the isobars described concentric circles round it, the inclination of the winds to the course of the isobars, at six stations within 100 miles of the centre, are found to be as follows :—

Station.	*Distance from centre.*	*Angles of W. Div. to Isobar.*
Calcutta ...	94 miles...	57°
False Point	72 " ...	30°
Midnapore	73 " ...	19°
Mutlah Light-ship	85 " ...	37°
Diamond Harbour	63 " ...	65°
Saugor Point	33 " ...	45°
	Average ...	42°

These angles shew the incurvature of the winds, and each direction may be considered as the resultant of a tangential and radial movement, the former of these components being proportional to the cosine, the latter to the sine of the angle. If we call this angle i, the angular movement u of the winds, which determines the centrifugal force in the formula for G, will be, not $\frac{v}{r}$, but $\frac{v \cos i}{r}$, and $v \sin i$ will be the movement directly towards the centre of the storm, or in the direction of the gradient and generated by the barometric difference.

136. Rainfall in a cyclone.—It is constantly noted in the logs of ships that traverse the Bay of Bengal, during the formation of a cyclone, that they experience a deluge of rain. A reference to any of the detailed reports on the cyclones described by Mr. Piddington, or by the Meteorological officers of Bengal during the last ten years, will afford ample verification of the statement; and, as will presently be seen, the fact is an important one in reference to the theory of their generation. Their approach to the land is also heralded by squalls of rain, more especially along the path of the storm, and it is very heavy during the passage of the vortex. In the central calm, however, fine weather seems generally to prevail. In the cyclone of the 5th October 1864, falls of 10 inches, 7·5 and 7·1 inches were recorded at three places, lying on the central track; while at places lying near it, to right and left, quantities varying from 2 to 4 inches were registered. In that of the 15th and 16th October 1874, 10 inches were recorded at Midnapore and 9·05 inches at Contai, both places being near, but not on the central track; and at other places further inland, over which the vortex passed, the fall varied from 3 to 7 inches. In the Vizagapatam

storm of the 7th and 8th October 1876, 15·2 inches fell at the above station in 18 hours, and the total quantity of rain recorded during the storm was 17·6 inches. At Vizagapatam, 15·6 inches fell. In the subsequent Backerganj storm, of the 1st November, only 5·12 inches fell at Noakhally in the path of the centre, and, for the most part, smaller quantities to right and left. This storm, however, broke up almost immediately on reaching the land.

While, however, the cyclone, both during its formation and its subsequent passage, is accompanied by very heavy rain, it is noticeable that, during the former period, there is little or no rain over the land around the Bay; at all events round the north of the Bay. This was very strikingly the case before the Backerganj cyclone above referred to. From the 22nd to the 29th October scarcely a drop of rain fell at any station in Bengal and its dependencies, and for some days prior to the 7th of the same month (the day of the Vizagapatam cyclone) such rain as fell was very light and partial. The same was the case for four days prior to the 15th October 1874, and a reference to the past registers of rainfall in Bengal shew this to be a general law, and one of important meaning, as will presently appear.

137. Temperature in Cyclones.—In the cyclones of the Bay of Bengal, there are no such changes of temperature as characterise the storms of extra-tropical regions. Throughout the storm and in all parts of it, the temperature is almost uniform; and, generally speaking, the average temperature of saturation for the time of year. In the October storms this is between 75° and 80°. There is a very obvious reason for this. It has been explained in the Introduction and § 51, that the Himálaya bars access to any polar wind currents; and the air which chiefly feeds the cyclone is drawn from the Bay of Bengal, the indraught from the land area around being comparatively small.

138. Electrical and other phenomena accompanying Cyclones.—During the formation of cyclones, lightning is commonly experienced, but during the passage of cyclones over the land it is rather the exception than the rule. The commonest form of electric discharge appears to be continuous and silent, as might be expected in a saturated atmosphere laden with water drops. The accounts received from places where a cyclone has passed in the night-time, make frequent reference to a light seen at different points of the horizon; and it is sometimes reported that villages were seen burning around; (generally a mere inference from the luminous appearance.) One description of the cyclone of the 5th October 1864 contains the following: "During

the night of the gale, numerous fires were raging in all directions; and in looking out upon the storm, the night was something beautiful to behold; a black mass, as it were, rushing past, with the sky above it perfectly red, as after a rosy sunset. The natives believe that the redness of the sky was caused by a meteor and not by the fires that were raging at the time." But the most graphic description referring to the same storm is that given by Captain Graham in the following words:—"On the 5th October, the wind had been blowing all day in stiffish squalls accompanied by rain, and its general direction was about east to south-east. At about 4 P.M., the wind went to north-east, and my manjees (boatmen) saying they could not make way against it, I anchored near the east bank of a low mud island in the river Jhenai, at a place called Shahgunj, latitude 24° 50,′ longitude 89° 48′. Between 8 A.M. and 9 P.M., the wind increased very much, blowing from north-east; and, finding the boat dragging, I let go a second anchor. There was then a slight lull; but a little after 10, on it came again, driving the boat on shore, and fixing her sternpost and rudder fast in the mud; when, the boat being unable to rise to the waves, they washed in over all and swamped her. We then jumped on shore and sat cowering on the mud under an old sail. Shortly after we landed, (say at about 11 P.M,) there was a decided lull, and after this, it came on again, veering to the north; at which point, I first observed a pale bright light on almost a level with the horizon. This light I observed accompanied the wind round to the north-west, where it stopped, and again began to move to the north-east. Thence it went round with the wind to the east and south-east, being sometimes high and sometimes low in the heavens; and finally about 1 o'clock on the morning of the 6th, it broke out in great splendour in the south-west, lighting up the whole sky, and appearing like the sun breaking through murky clouds at mid-day. The country was partly lit up, and I thought the day had broken; but after about half an hour the light disappeared and left everything as dark as ever."

The most probable explanation of this phenomenon is that, it is of the nature of the glow discharge, such as takes place from the extended surface of a charged electric conductor in a dark room where no other conductor is in its immediate neighbourhood, and also in rarified gases. But another very different form of electric discharge, *viz.*, ball-lightning, is not unfrequently recorded also.

That electricity is copiously generated during a cyclone by friction is extremely probable, but that it plays any important part in determining the formation of cyclones, seems to me a quite groundless supposi-

tion. It appears to be rather a penultimate condition of the energy of the storm, before it undergoes its final degradation into that of diffused heat.

Another phenomenon of common occurrence in connection with cyclones, and frequently regarded as a prognostic of these storms, is a brilliant red colouring of the whole sky before sunrise or after sunset. A somewhat similar appearance is noticed in the accounts above quoted; but as an accompaniment of the cyclone, and as occurring during the night time. The source of the light is doubtless very different in the two cases, but the characteristic redness is most probably in both cases explicable by the fact that, at the times when the phenomenon is observed, the whole atmosphere is highly charged with vapour at or near saturation; and the peculiar selective absorption of vapour for light rays of high refraction has already been noticed in the note to § 24.

139. Seasons of Cyclones.—The seasons at which cyclones are more especially prevalent, are those of the change of monsoons. But they are much more prevalent at the close of summer monsoon than at its beginning, and they occur occasionally during its prevalence in the Bay of Bengal; all of which facts are susceptible of a simple explanation, as will be seen in the sequel. Taking Dr. Buist's catalogues as a basis, I have collected notices of 115 cyclones in the Bay of Bengal, the distribution of which in the several months of the year is as follows:—

	Cyclones.		Cyclones.
January ...	... 2	July ...	... 3
February ...	... 0	August ...	... 4
March ...	... 2	September ...	... 6
April ...	... 9	October ...	... 31
May ...	... 21	November ...	... 18
June ...	... 10	December ...	... 9

In this list, every case in which a storm has been formed in the last days of one month and has lasted into the beginning of the following month, has been reckoned to the month in which the storm was generated. The list includes storms as far back as 1737, when a furious hurricane, accompanied by a violent earthquake, raged at the mouth of the Ganges, and reached 60 miles up the river. It is said to have destroyed 20,000 craft of all descriptions, and the storm-wave rose 40 feet. It is recorded that 300,000 people perished in Lower Bengal or in the Bay; but, judging from the character of Indian statistical estimates, even at the present day, we may perhaps justifiably entertain a suspicion that these figures are somewhat excessive.

The list shews that February is the only month in which no cyclone is recorded; and it is well known from Mr. Meldrum's researches, that this is the month of their greatest frequency in the South Indian Ocean. The two January storms occurred in the latitude of Ceylon, which is about the most southerly limit at which, in the northern hemisphere, cyclones are ever formed. The two March storms affected the coast of Madras, but both occurred in the last week of the month. Those of the last half of November and December, and those of April, with two exceptions, were restricted to the southern half of the Bay. These exceptions both occurred in the last week of the month. In May and in October and the first half of November, storms are about equally frequent in all parts of the Bay; but all those recorded from June to September were, with a single exception in June, restricted to its northern half. Thus, it appears that the zone, in which cyclones are prevalent, travels north and south with an annual oscillation; not, however, exactly with the dividing line of the monsoons, for we have seen in § 91, that, north of the equator, the line of separation of northerly and southerly winds travels from north to south at both seasons of change. And herein we have the undoubted explanation of the fact, that cyclones are about twice as numerous at the end of the summer monsoon as at its beginning; for we have seen in § 87, that in March, the Bay of Bengal is on an average a region of relatively high pressure, with an anticyclonic circulation of the wind; whereas, in October, it is a seat of low pressure circumscribed by higher pressures, and the circulation of the wind is consequently cyclonic.

In the China seas, where the sea is not limited to latitudes below 22°, the whole season of the summer monsoon is characterised by frequent cyclones, and the month of their greatest frequency appears to be September. And having regard to the facts detailed in § 123, we may say that, strictly speaking, the whole of the summer monsoon is equally a cyclone season in India; but the cyclones, being chiefly formed on land, do not attain to any degree of violence; so that, until charted, and seen to be essentially cyclonic in constitution, their real character escapes recognition. The recorded cyclones of the Arabian Sea are too few to allow of any generalisation of value with reference to the periods of their occurrence. It is probable, however, that in this respect they follow the same general laws as those of the Bay of Bengal.[1]

[1] I find records of 17 storms generated in the Arabian Sea (exclusive of those which have crossed from the Bay of Bengal); of these, three occurred on the Arabian coast between the Cooria Mooria Island and the Gulf of Aden. With respect to season they were distributed as follows: April 3, May 1, June 5, September 1, October 2, November 3 and December 2.

140. Cyclical variation of cyclone frequency.—It is well known that Mr. Meldrum has detected in the records of cyclones in the South Indian Ocean, and Mr. Poey in those of the West Indies, a very distinct cyclical periodicity, coinciding with that of sun-spot frequency; and the former has shewn that years of maximum sun spots are also those of most numerous cyclones and also apparently of their greater average size. The records of the storms in the Bay of Bengal are too imperfect to admit of any satisfactory investigation on this head. The following is a numerical list of those I find on record, during the last forty-seven years:—

Years.	Cyclones.	Years.	Cyclones.
1830	2	1854	2
1831	2	1855	1
1832	2	1856	2
1833	1	1857	1
1834	2	1858	3
1835	0	1859	3
1836	2	1860	No records.
1837	0	1861	No records.
1838	2	1862	No records.
1839	4	1863	No records.
1840	2	1864	3
1841	1	1865	1
1842	3	1866	0
1843	2	1867	3
1844	2	1868	1
1845	1	1869	4
1846	2	1870	3
1847	0	1871	1
1848	3	1872	4
1849	2	1873	1
1850	3	1874	9
1851	2	1875	0
1852	1	1876	2
1853	1		

The years 1837, 1848, 1860 and 1870 were those of maximum spots. In 1874, the storms recorded by Mr. W. G. Willson are in several instances little local storms, such as would hardly have attracted attention, but for the exercise of a keen scrutiny. There is no certainty that all the storms that have occurred have been recorded, and the absence of any records for the years 1860-63 leaves a gap at one of the periods of maximum which much impairs the value of the result.

141. Geographical distribution of cyclones in Indian seas.—Cyclones are rare in the Arabian Sea, much more common in the Bay of Bengal, and most frequent in the China seas. To the south of the

equator they are common in the South Indian Ocean, where they have been made the subject of a special study by Mr. Thom, and, in recent years, by Mr. Meldrum. But they never occur within 6° or 7° of the equator in either hemisphere. The storm that occurred at the end of November 1843, described by Mr. Piddington in his eleventh memoir, appears to have been generated as low down as 6° north latitude; and it is interesting to note that, at the same time, in 7° or 8° south latitude, another storm was formed, revolving, of course, in the opposite direction, and travelling to the south-west, while the former travelled to the north-west. In the Bay of Bengal, they are most commonly formed in the middle or eastern half of the Bay,—and the sea to the west of the Andamans and Nicobars, more especially, is the cradle of some of the most destructive storms that have ravaged the coasts of India. Sometimes, however, they are formed a few hundred miles to the east of Ceylon, but very rarely under the lee of the Indian coast. Storms are also formed in the Andaman Sea, to the east of the islands of that name; and, in such case, they sometimes take a northerly course up the Gulf of Martaban. Mr. Piddington records several of those storms; and one passed over the island of Narcondum in October 1872, levelling the forest which covers this extinct volcanic cone.

In the Arabian Sea, most of the storms recorded have either been formed in the neighbourhood of the Lakhadivhs, or between those islands and the Indian coast; but some, which have originated in the Bay of Bengal, have crossed the Peninsula on a westerly course, and have been traced far out into the Arabian Sea. Such was the cyclone described by Mr. Piddington in his eighth memoir, which was formed in the neighbourhood of the Andamans, about the 22nd October 1842, and travelled thence to Pondicherry; after which, crossing the Peninsula, it passed out by the Palghat Gap, and was afterwards traced to east longitude 60°, on the 1st November, having completed a course of 2,000 miles and lasted 9 days.

142. Tracks of Cyclones.—It is well known that in the Caribbean sea and the North Atlantic, and also in the South Indian Ocean, cyclones pursue a parabolic course; diverging from the equator, and moving at first westward, and afterwards recurving in the neighbourhood of the tropics and passing off in an easterly direction. In the Bay of Bengal, the limits of the sea do not reach to the Tropic of Cancer, and the course of the cyclones is almost invariably between west and north; but those which attain the coast of the Sunderbans, generally become more or less easterly in their further course across Bengal. There are a few exceptions on record, in which, the course of the

storm over the northern part of the Bay has been somewhat to the east of north, but they are rare; and hence, while the Indian coast is greatly exposed to their ravages, the coast of Arakan is but very rarely visited by them. The most important exception on record is that of the late disastrous Backerganj cyclone of the 1st November 1876; the history of which has been worked out with great skill by Mr. John Elliott. A small cyclone also passed over Akyab in November 1868, but the place of its formation is not known; and two are recorded by Mr. Piddington at Khyouk Phyoo, *viz.*, in May 1834 and November 1838. In a few cases,—for instance, those of the storms of October and November 1842,—the tracks have been west throughout; and Mr. Piddington has charted those of two storms which appear to have followed the unusual directions west-by-south and west-south-west.

143. The origin of cyclones.—The cyclones of the Bay of Bengal originate when there is no current of wind blowing in any definite direction across it; when the atmosphere is calm or moved only by light and variable winds; and when, as Mr. Elliott has lately shewn, the pressures are equal, or nearly so, all round the coasts. These conditions evidently preceded the Midnapore and Burdwan cyclone of October 1874, and also the Balasore cyclone of June–July 1872, both described by the late Mr. Willson, as well as the two cyclones of October 1876 described by Mr. Elliott, and, indeed, all that I have examined and for which the requisite data are given. Another condition which appears to be equally characteristic of the formation of cyclones is, that, during their formation, but little rain falls on the east and northern coasts of the Bay, and in Bengal. On the other hand, ships that are crossing the middle of the Bay, the place of a cyclone's origin, at such times, invariably meet with torrential rain, and an atmospheric pressure lower than that around the coasts. Ample evidence of this will be found in the various reports that have been published by the Bengal Meteorological Office of late years, and in some of Mr. Piddington's Memoirs. Lastly, a squally westerly wind prevails in the neighbourhood of the equator; which, when a barometric depression has been formed in the Bay, blows in towards it, and becomes the main feeder of the storm. Light easterly or north-easterly winds are felt at the same time in the north of the Bay and in Bengal, but these are very light, not exceeding two or three miles an hour, until the cyclone is fairly formed, when their velocity increases with the increase of the barometric gradient.

The hypothesis of the formation of cyclones to which the above facts point, which has been put forward in the Appendix of a paper on "The Winds of Northern India" and elsewhere, and with a slight modi-

fication adopted by Mr. Elliott as the result of his investigation of the storms of 1876, is, that the primary cause of cyclone formation is "the production and ascent of a large quantity of vapour, which is condensed with the liberation of its latent heat over the place of its production, instead of being carried away to some distant region", and the consequent local lowering of the atmospheric pressure; causing or tending to cause an indraught of air towards the place of minimum pressure. This, I believe, is also the view of Reye, Loomis and Mohn; but the Bay of Bengal is almost the only sea which readily admits of its verification by direct observation.

An indraught of air once set up, a cyclonic circulation will follow, in consequence of the earth's rotation, according to the principles enunciated in Ferrel's law; and as the velocity of the circulation increases, the centrifugal force of the circulating currents will partly equilibriate that difference of pressures between the centre and periphery of the cyclone, which is produced by the ascent of the convection current over the vortex; this current, again, depends on the density of the air of the vortex being kept low, by the constant evolution of latent heat from the condensed vapour. According to this view, the centrifugal force of the circulating currents partly neutralises that of the barometric gradient, and retards the inflow of air to restore barometric equilibrium; and the earth's rotation, by impressing on every part of the current, in the northern hemisphere, a tendency to deviate to the right (*i. e.*, radially from the centre of cyclone) also neutralises a portion of the gradient.

144. The source of a cyclone's energy.—But it would be an error to regard either of these forces as the *cause* of the low pressure in a cyclone; if, by that term, we imply that they are *independent* sources of energy, capable of producing or adding to the potential energy of the barometric gradient. On the contrary, it is only in virtue of their momentum that the circulating currents either exercise centrifugal force or tend to deviate in a radial direction under the influence of the earth's rotation; and the kinetic energy of that momentum is derived immediately from the potential energy of the barometric gradient. The momentum of the revolving earth is unaffected by wind currents, which, on the west of a cyclone, tend to deviate to the west, and on its eastern limit tend to deviate to the east, and therefore the earth neither loses nor gains in kinetic energy. Nor is there any source of energy, kinetic or potential, (at least, none has ever been suggested,) from which the air can derive the energy of its motion, other than the ineqality of pressures within and without the vortex. This potential

energy requires, however, constant renewal, for, since air is constantly pouring into a cyclone, and, passing upwards in a convection current, after which it is dispersed in an anti-cyclone in the upper atmosphere, in order to maintain the vortex, momentum, which is a form of energy, must constantly be imparted to the air newly set in motion, to replace that which has flowed away; and, furthermore, the friction of the whole system represents a constant degradation of the energy of the storm. No source of energy competent to supply these demands, other than the latent heat of the condensed vapour has yet been pointed out; but that this source is competent and even ample, has been shewn by a calculation of Professor Reyes in the case of the Cuba hurricane of the 5th to 7th October 1844.

A firm grasp of the above application of the doctrine of energy to the case of cyclones will enable us to detect what, to my view at least, is the fallacy of two hypotheses, which, at different times, have been put forward by writers, whose contributions to the phenomenal laws of cyclones have justly won for them foremost places in the ranks of Meteorological authors. One of these relates to the path of the winds in a cyclone, the other to the mode of the storm's origin. The first is the circular theory of Reid (not Redfield) and appears to have been lately revived by M. Faye.[1] The other is the parallel current hypothesis, as I understand it, of Mr. Meldrum.

145. Circular theory of Reid.—I have already pointed out that, in numerous cases of cyclones, that have been laid down on charts from the recorded direction of the winds, the course of the currents proves to be a spiral, and in some cases a very sharp spiral. Mr. Meldrum has established the same fact in respect of the cyclones of the South-Indian Ocean. But in certain cases, as in some of the storms recorded by Reid and Piddington, the direction of the winds appears to have deviated only a few degrees from a tangential direction, and it is difficult enough to judge of direction to within a point or two when a ship is involved in a furious storm. Some doubt may still, therefore, be entertained whether the winds do not sometimes revolve in a truly circular path, or, even as Mr. Piddington thought possible, sometimes be, to a certain extent, centrifugal, unless it can be shewn that such conditions are inconsistent with mechanical principles.

If the path of the winds is in a true circle, we have by Ferrel's law, [§ 133]—

$$\Delta B = (2n \sin. \phi + u)\, v \times const.$$

that is, the radial force of the barometric gradient is exactly equi-

[1] I have not, however, seen Mr. Faye's original paper; but only the abstract given in "*Nature*."

libriated by the centrifugal force and that of deviation combined. Since the isobars around a cyclone are closed curves, the winds must either blow along the course of an isobar, (if its form be circular,) or must cross it twice; in which case, during a part of their course, they must blow from a place of lower to one of higher pressure; which implies a loss of energy of exactly the same amount as is gained in the course from the higher to the lower pressure, supposing there to be no friction. If they blow along the course of the isobar, they will be under the same pressure throughout; and, in neither case, is there any accelerating force; in other words, any supply of energy to overcome the retardation of friction. Since, however, no current of air can be set in motion without friction, the winds so blowing must be retarded and eventually brought to rest, and the continuance of a cyclone, much more its production under such circumstances, is therefore a mechanical impossibility.

The case, supposed by Mr. Piddington, of the winds being to some extent divergent, is, *à fortiori*, inconsistent with the distribution of pressures in a cyclone; unless it can be shewn that the energy of their motion is derived from some source independent of the potential energy of the barometric gradient; and, as far as I am aware, no one has ever pointed out any such source, nor can I conceive any such. We may then conclude that a certain incurvature of the winds is the only condition under which a cyclonic vortex can be maintained.

146. Theory of parallel winds.—The hypothesis that cyclones are generated between parallel currents, flowing side by side, but in opposite directions, has been put forward by Dr. Thom, and also by Mr. Meldrum. If, indeed, nothing more be implied in this hypothesis than that, between two such currents, there is an area in which the air has no motion; and in which, therefore, the products of evaporation are condensed over the spot where they are produced, it is unobjectionable; but it then becomes only a particular case of that put forward in § 143. But as some of those who hold it seem to regard it as an alternative and rival theory of cyclone genesis, this fact seems to imply that the deviation of opposite parallel currents, of moderate velocity, under the influence of the earth's rotation, is regarded as capable of producing such a reduction of local pressure as shall give rise to a cyclone of destructive violence.

Let us contemplate the case of two opposite parallel currents of equal velocity in the same latitude, which is evidently the case in which, for any given velocity, the greatest barometric depression will be produced in the intervening zone. It is clear that the source of the energy of

their motion is the existing barometric gradients which cause them; however these may have been originally produced. But the barometric depression between them (which is a form of potential energy) is produced, according to this view, at the immediate expense of their momentum; for the earth's rotation merely tends to alter the direction of the currents and furnishes no energy; and therefore, the potential energy of the barometric gradient produced by their deviation, (according to Ferrel's law,) is, at the utmost, so much transferred from that of the original gradient. By no possible process can the barometric depression, so produced, give rise to currents having greater energy than the original parallel currents. But it is doubtful whether even this transfer takes place; whether the double gradient producing the parallel currents, and that which is maintained between them, are not identical; whether, in short, the deviation of the currents is not simply a conservative action, which prevents a rapid restoration of pressure equilibrium. As far as I know, nothing has ever been shewn to the contrary, and it is the simplest and most consistent explanation of the phenomenon.[1]

147. Cyclone prognostics.—From the facts detailed in §§ 134, 136, 139 to 144, we may draw certain rational conclusions as to the signs of cyclone formation in the Bay of Bengal. In the first place, their formation demands that no strong steady current shall carry away the products of evaporation; and this implies that there shall be, in the first instance, a tolerably uniform pressure over a large portion of the Bay, and no general gradient from the Bay towards the coasts. This state of things is generally indicated by the uniformity of the pressures round the coasts, with light winds, which tend to circulate around the Bay, being southerly on the Arakan coast, easterly in Bengal, and north-easterly or northerly on the coast of Orissa. The pressure to the south, in the neighbourhood of the equator, is higher, and the winds are here squally and from the west. Westerly winds also prevail in Ceylon. Heavy and continued rain falls over the cyclone cradle; but, around the coasts and in Bengal, but little rain falls; while the sky gradually clouds over with cirro-stratus; and, after a time, long low masses of fracto-cumulus drift in the direction of this prevailing wind. If the cyclone is forming in the south of the Bay, the barometer in Bengal is but little affected, or at the utmost falls but slowly, until the cyclone approaches;

[1] The whole subject of the mechanics of cyclones is now being treated in an admirable and comprehensive manner by Professors Guldberg and Mohn, in their work, "Etudes sur les mouvements de l'atmosphère," Christiania, 1876; and to that work I would refer the student who is desrious of a more intimate acquaintance with this important branch of meteorology. As yet, the first part only has reached me.

but if in the north of the Bay, as is the case more especially when they occur in the months of June, July, August and September (sometimes also in May and October), the barometer falls steadily during the formation of the vortex.

In judging of the probability of a storm, these prognostics must be taken in conjunction with general considerations of the season of the year. Cyclones are unknown in the north of the Bay, from the middle of November to nearly the end of April. In March, indeed, the pressures are frequently very uniform around the northern and western shores of the Bay; but they are higher in the Arakan coast, and any circulation of the winds is anticyclonic. Sometimes strong winds, almost gales, blow from the south on the shores of Bengal; but they extend to no great distance at sea, and have no ominous import. However strongly the winds may blow on the shores of Bengal and in Orissa, *if they are from south, with any westing in them, there is no fear of a cyclone.*

Calm, close weather in May, June and October, on the Bay and its coasts, is always treacherous; and an unsteady summer monsoon in Bengal is also sometimes ominous of storms; but cyclones are very rare in July, August, and the first half of September.

148. The storm-wave.—Great as is the destruction of life and property, both on sea and land, wrought by the blast of the hurricane, all such disasters as shipwrecks and homesteads devastated by the wind are utterly overshadowed and eclipsed by the fell sweep of the storm-wave. It is probable that every cyclone is accompanied by a storm-wave. The reduction of atmospheric pressure at the centre of the storm, amounting sometimes to two barometric inches, would of necessity cause a rise of the mean level of the sea, amounting to about 13 inches for each barometric inch of diminished pressure; and, in addition to this, the winds, in virtue of their friction on the sea surface, and the spiral incurvature of their course, must tend to pile up a head of water in the central part of the vortex. But it is only when the wave thus formed reaches a low coast, with a shallow shelving foreshore, such as are the coasts of Bengal and Orissa, that, like the tidal wave, it is retarded and piled up to a height which enables it to inundate the flats of the maritime belt, over which it sweeps with an irresistible onset. As might have been anticipated, the destructiveness in each case depends very much on the phase of the tide at the time of the storm-wave's approach, and also on the phase of the moon; since, if a storm-wave arrives at the time of flood during the height of the spring-tides, the

effects are cumulative, and the depth of the inundation and the extent of the destruction so much the greater. But if it arrive at the time of low water in the springs, its effects may be to some extent neutralised. Its full effects are most felt on the right of the central track of the cyclone, for the direction of the wind there coincides with the advance of the wave; whereas, on the left of the track, the wind generally opposes its advance. But the acme of its destructive power is displayed where a broad, shallow river estuary stretches up into the land to the right of the storm track,—estuaries, for instance, such as the Hooghly and the Megna, in which the tidal wave is ordinarily heaped up and retarded, forming a bore. Under such circumstances, the flats around these estuaries have become the theatre of the greatest natural catastrophes recorded in history;[1] for as such they may be estimated, even after due allowance has been made for the imperfection of Indian statistics, and the irresistible tendency of the unscientific mind to exaggerate all great disasters.

Mention has already been made of the storm of the 7th October 1737, in which the storm-wave is said to have risen to 40 feet in the Hooghly, sweeping away 300,000 souls. In May 1787, at Coringa, near the mouth of the Godavery, a storm-wave is said to have swept away 20,000 souls; and the storm of the 31st October 1831, which passed between Balasore and Cuttack, was accompanied by an inundation which destroyed 300 villages and 11,000 people. In the Calcutta cyclone of the 5th October 1864, the storm-wave inundated the flats on both sides of the Hooghly estuary, causing a loss of life, which a subsequent census (in part an estimate only) put at about 48,000 souls and considerably upwards of 100,000 head of cattle. The height of the storm-wave at Cowcolly Light-house was 16·48 feet above the level of high spring-tides, and this was about its greatest rise. At Kedgeree it was 15·9 feet, at the mouth of the Huldi river 10 feet, at Diamond Harbour 11·9 feet, and at the junction of the Roopnarain and Hooghly also 11·9 feet above high spring-tide level. The resulting inundation had a depth of from 15 feet downwards, over the land surface, and over a tract from 4 to 10 miles broad, extending from the banks of the river inland; the destruction was extreme.

But even this great disaster was eclipsed by that of Backerganj on the night of 31st October and 1st November 1876. This was not the first catastrophe of the kind that has ravaged this part of Bengal, even

[1] The three regions in which the greatest destruction of life has been caused by storm waves are the estuaries of the Hooghly and the Megna, and the flats of the Godavery delta, near Coringa.